

First Measurement of Double-Differential Charged Current ν_{μ} -Argon Scattering Cross Sections in Kinematic Imbalance Variables

Afroditi Papadopoulou

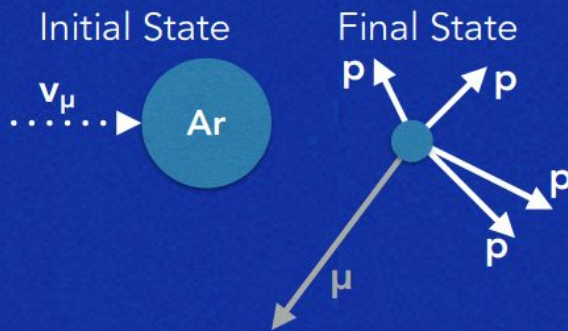
On behalf of the  collaboration

NuINT 2022

10/26/2022

μ BooNE

Color scale shows deposited charge



10 cm

BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

- Largest available neutrino-argon data set with ~500k recorded neutrino interactions

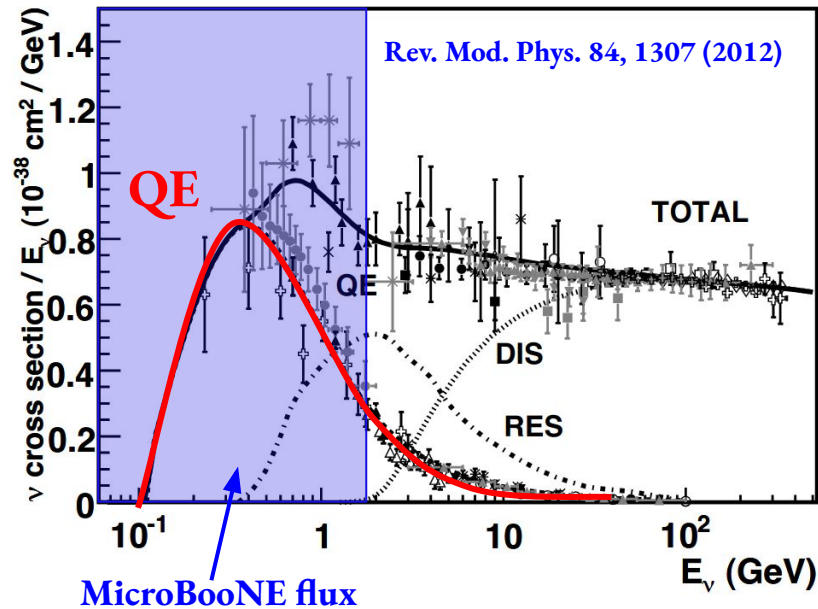
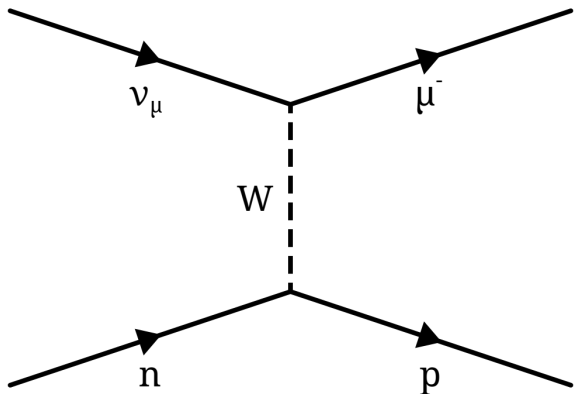
- ~40 published and active cross-section analyses

See talks by [L.Cooper-Troendle](#), [A.Szelc](#), [M.Kirby](#), [R.Fine](#), [C.Thorpe](#)

- Many focus on topologies with protons

See talk by [M.Kirby](#) (2 proton analysis)

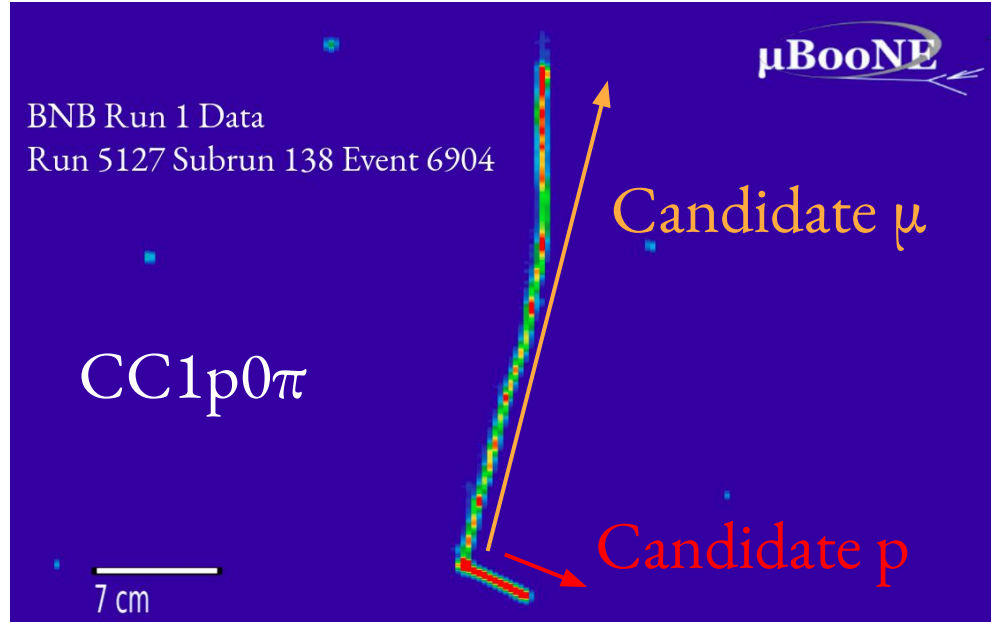
Charged Current Quasi-elastic (CCQE) Interactions



- Simple single muon-proton events
- Dominant at MicroBooNE energies

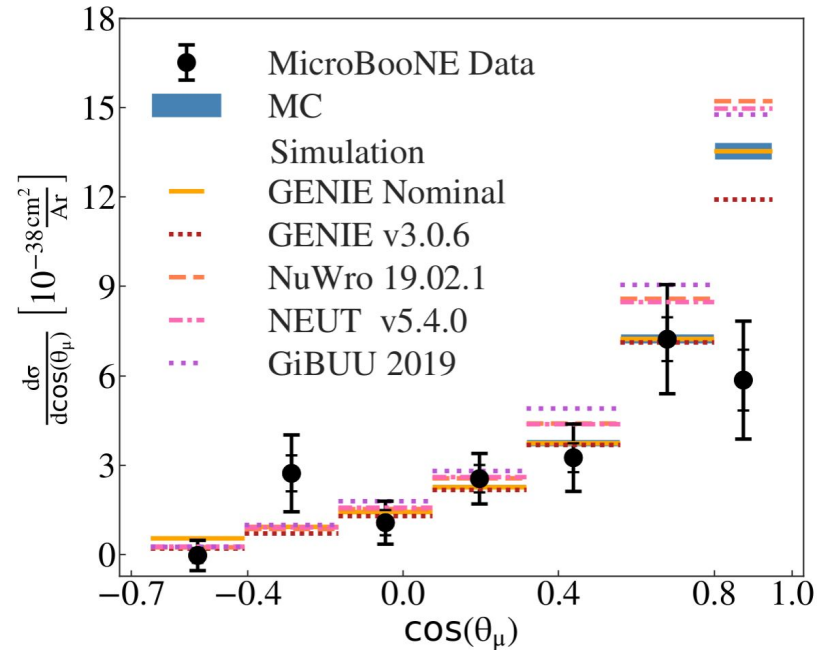
Quasielastic-like Signal Definition

- 1 muon ($P_{\mu} > 100 \text{ MeV}/c$)
- 1 proton ($P_p > \mathbf{300 \text{ MeV}/c !!!}$)
- No π^{\pm} ($P_{\pi} > 70 \text{ MeV}/c$)
- No π^0



Previous Results

- First measurement of neutrino-argon CCQE-like cross sections
- Powerful cosmic background rejection and high CC1p0 π signal purity
- Need for improved modeling!

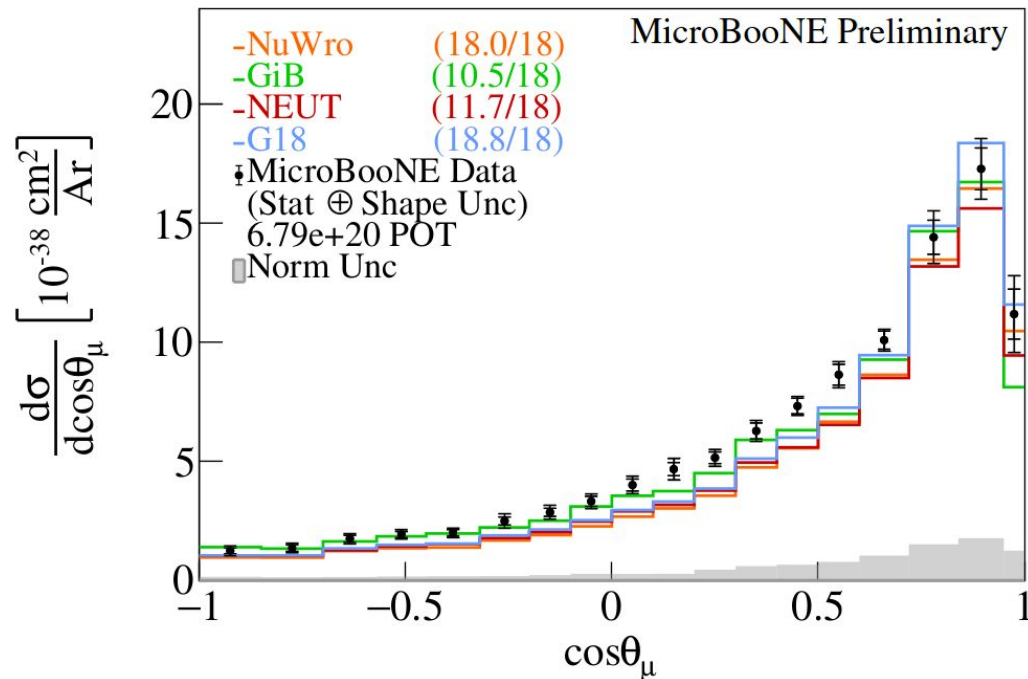


Phys. Rev. Lett. 125, 201803 (2020)

New MicroBooNE Results*

G18 = GENIE v3.0.6 G18_10a_02_11b
+ T2K Tune

- Higher statistics (x30)
Phys. Rev. Lett. 128, 241801 (2022)
Phys. Rev. Lett. 128, 111801 (2022)
- Improved signal processing
JINST 13 P07007 (2018)
- Reduced systematics
Eur. Phys. Journal C 82, 454 (2022)
- Improved modeling
Phys. Rev. D 105, 072001 (2022) [T2K tune]
EPJ Special Topics vol. 230, p. 4449–4467 (2021)

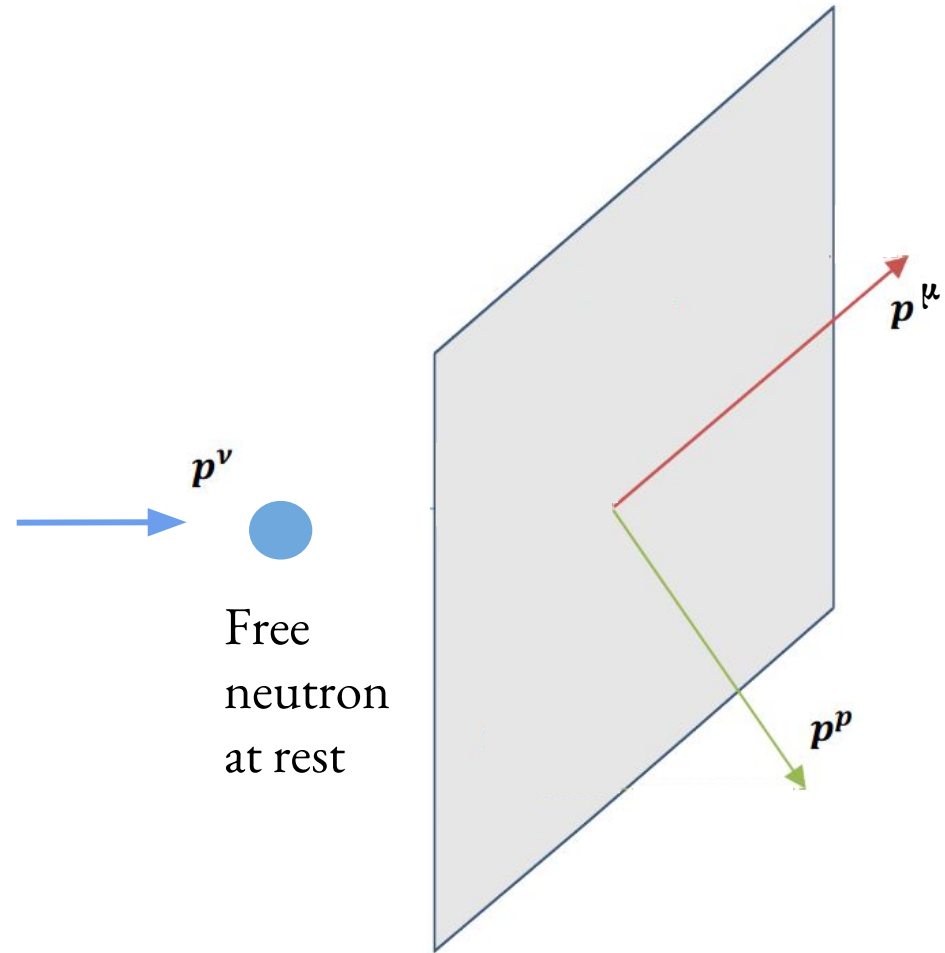


Now look at kinematic variables to
isolate specific nuclear effects!

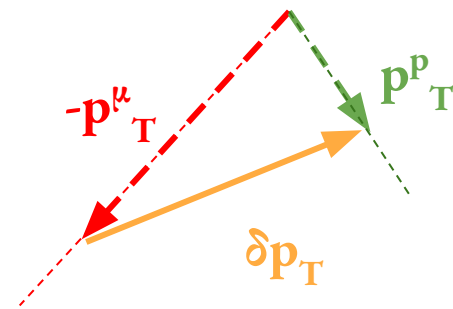
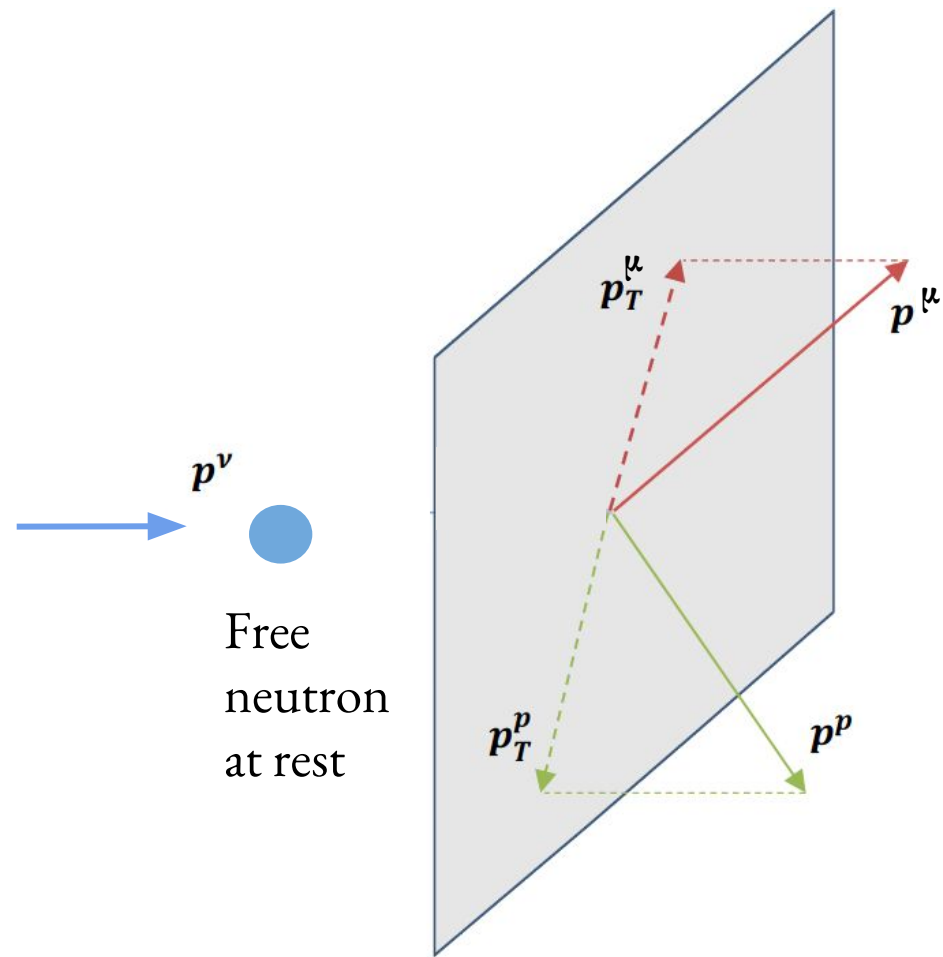
MICROBOONE-NOTE-1108-PUB (2022)

* See backup slide 21 for analyses differences

Transverse Kinematic Imbalance (TKI)



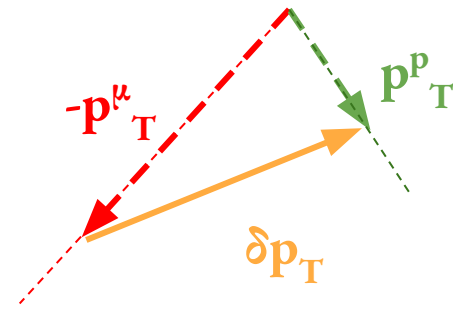
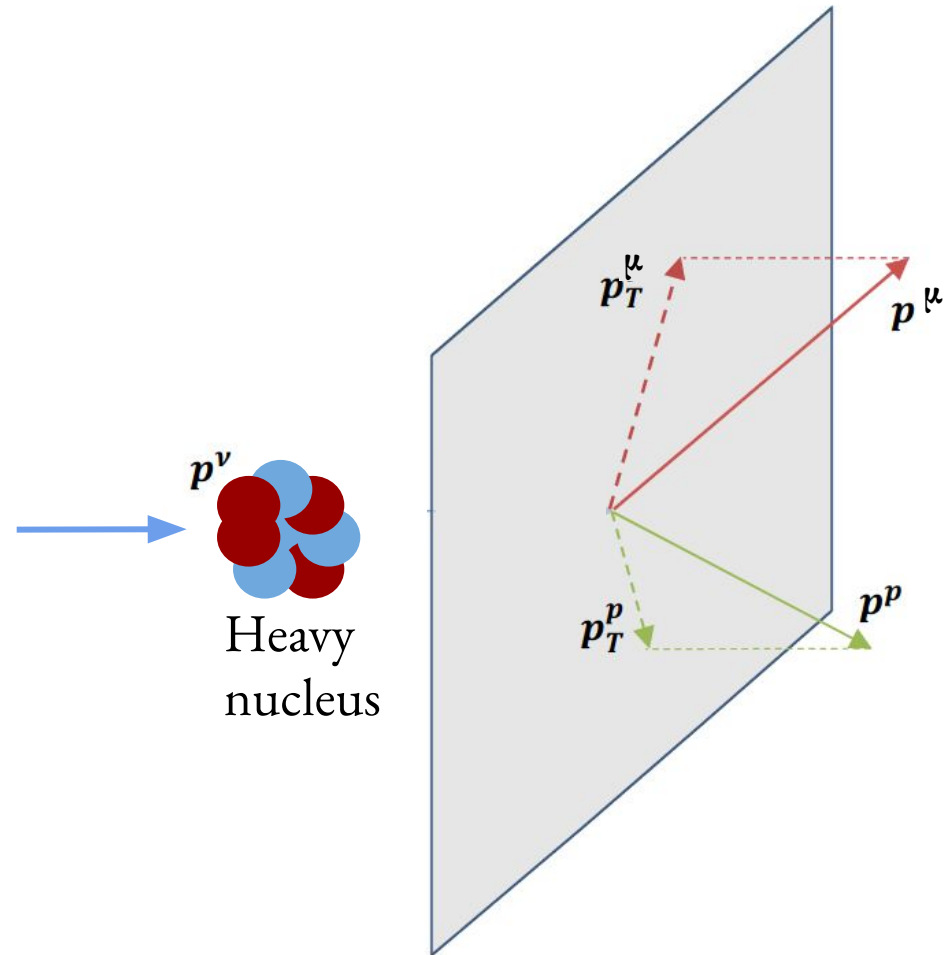
Transverse Kinematic Imbalance (TKI)



- $\delta p_T = |p_T^\mu + p_T^p| = 0$

Transverse projections
equal and opposite due to
momentum conservation

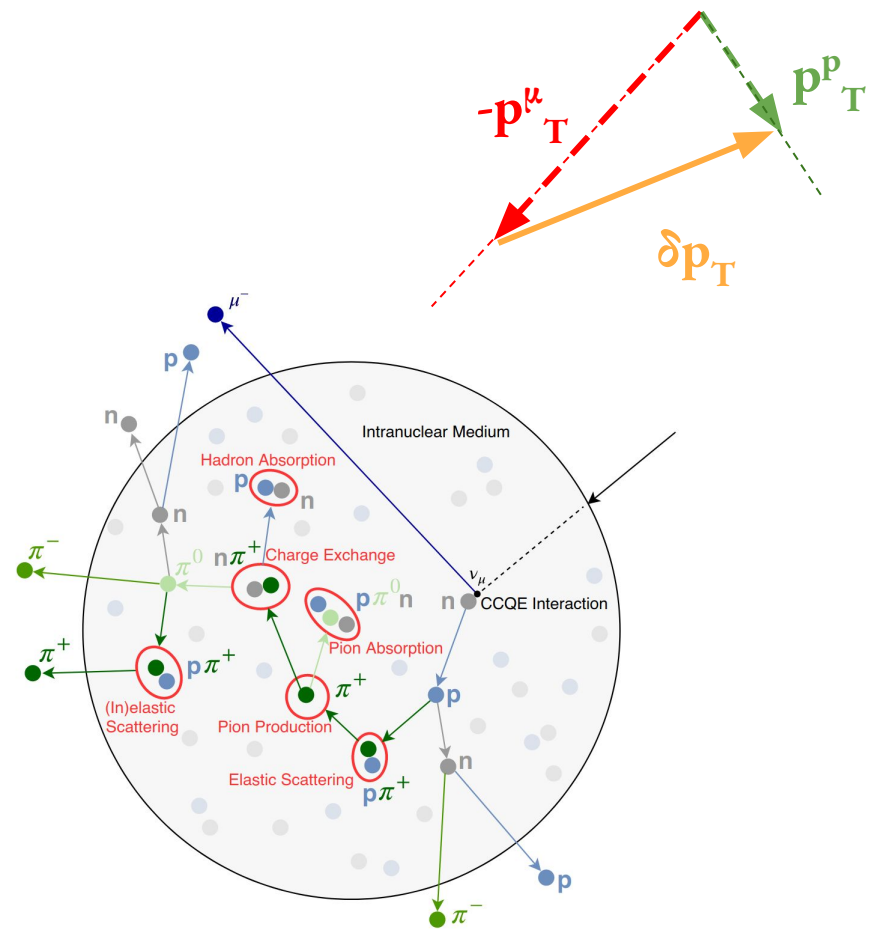
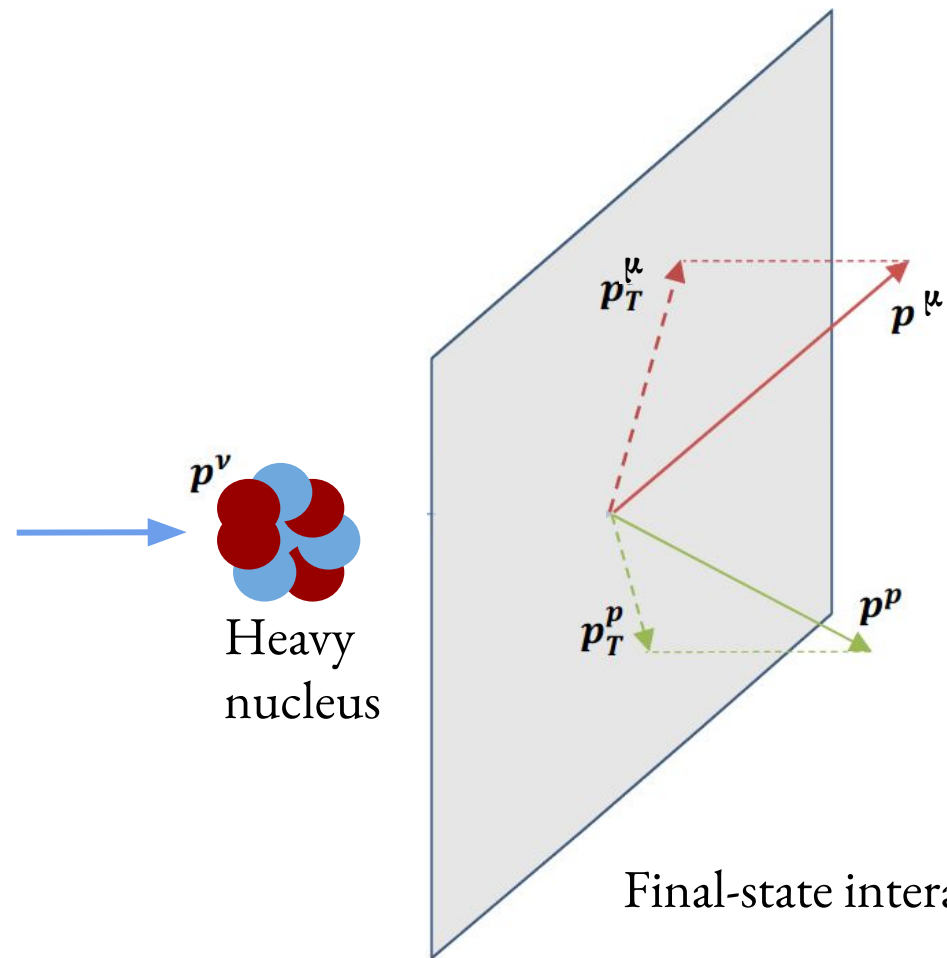
Transverse Kinematic Imbalance (TKI)



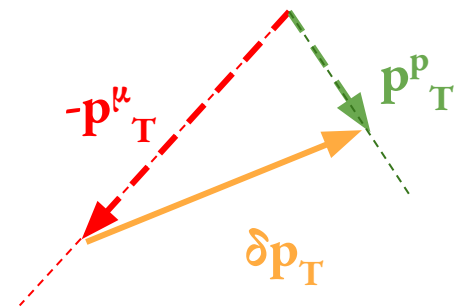
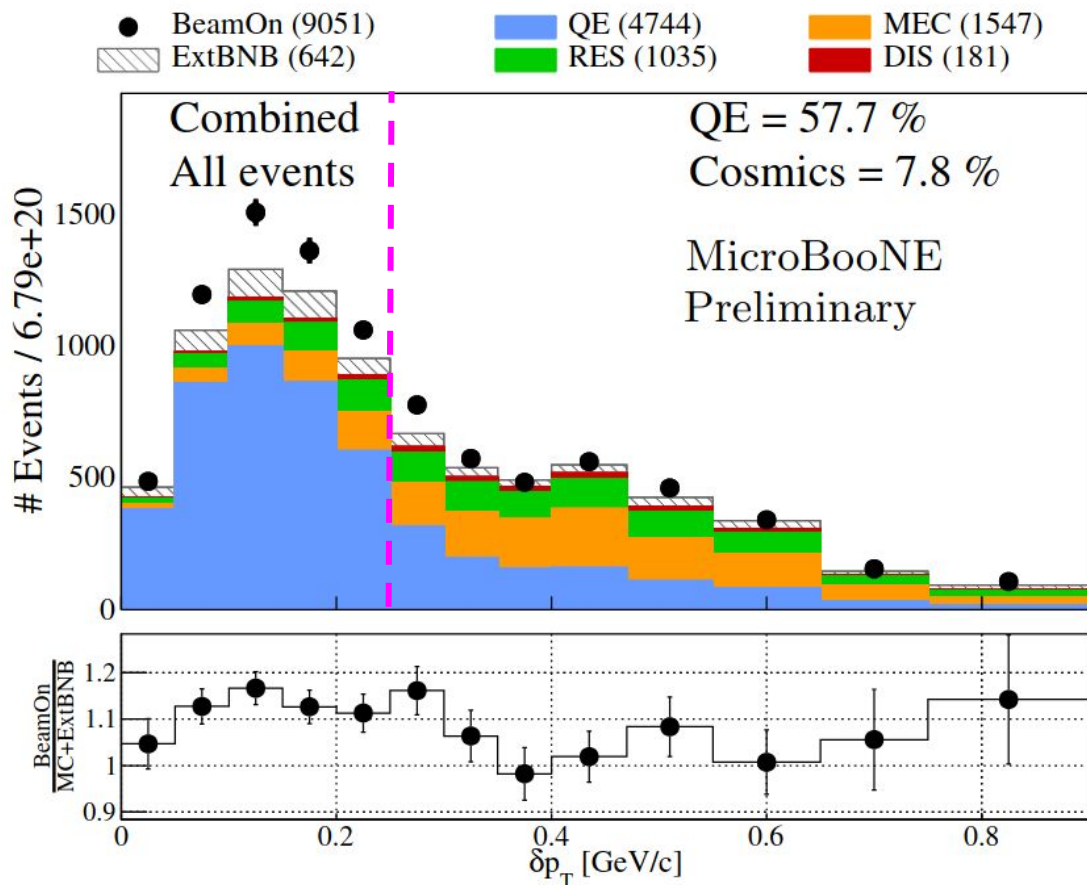
- $\delta p_T = | \mathbf{p}_T^\mu + \mathbf{p}_T^p | > 0$

Transverse missing momentum
due to initial nucleon motion
and other nuclear effects

Transverse Kinematic Imbalance (TKI)



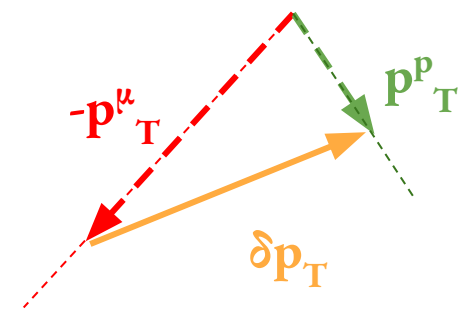
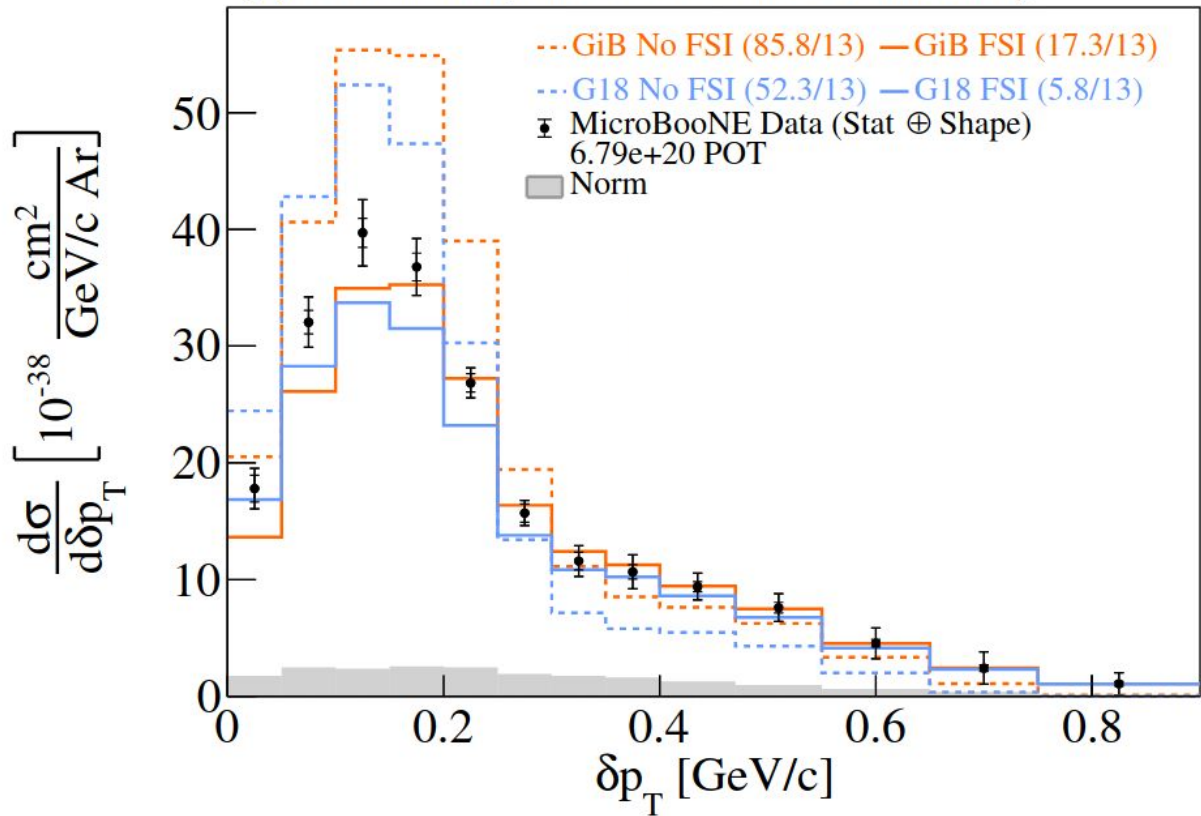
Transverse Missing Momentum δp_T



- **QE** dominance in peak below Fermi momentum (~ 250 MeV/c)
- **MEC/RES** mainly in high momentum tail

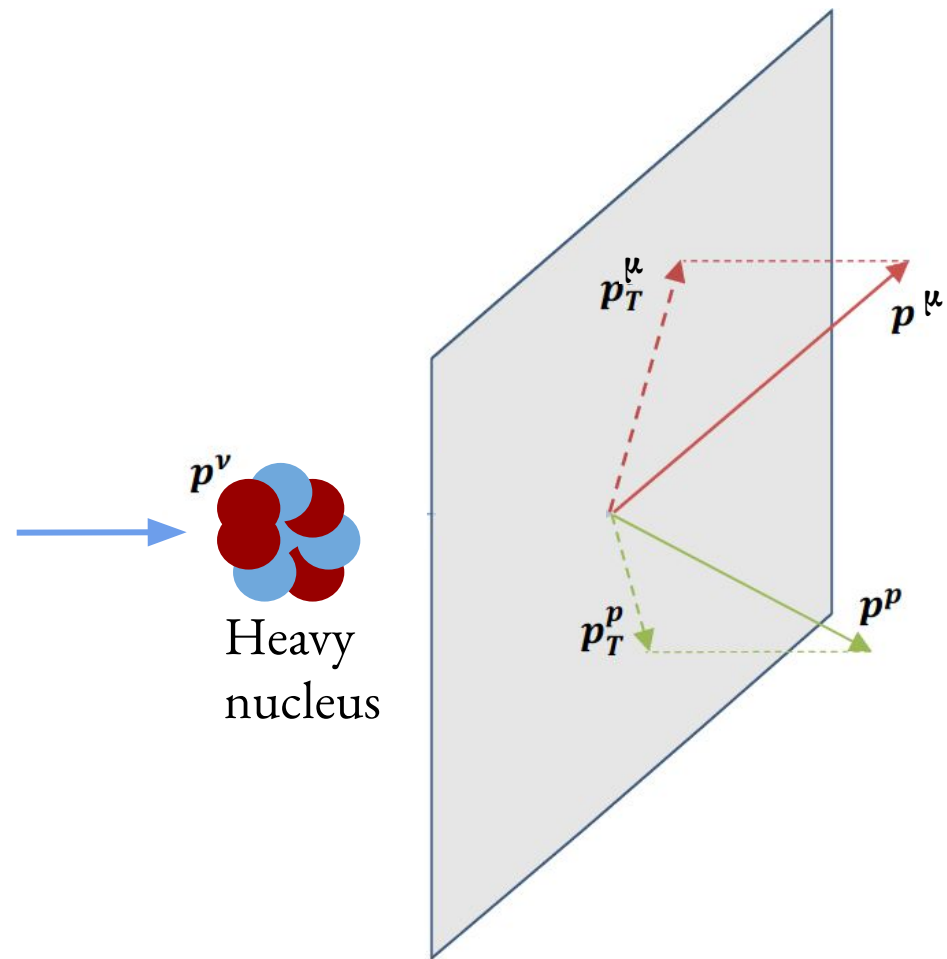
Transverse Missing Momentum δp_T Cross Section

All events, MicroBooNE Preliminary

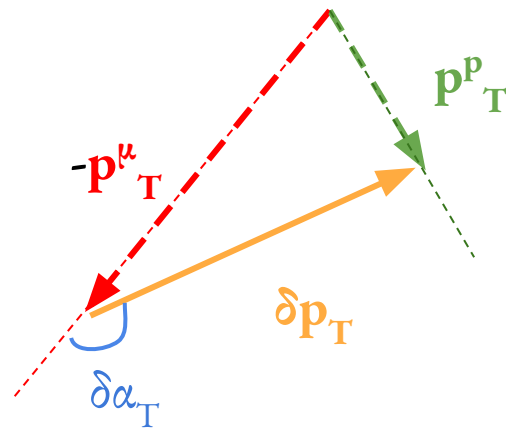


- First neutrino-argon differential cross section in δp_T
- Sensitive to initial nucleon motion & proton FSI modeling
- Data favors FSI addition

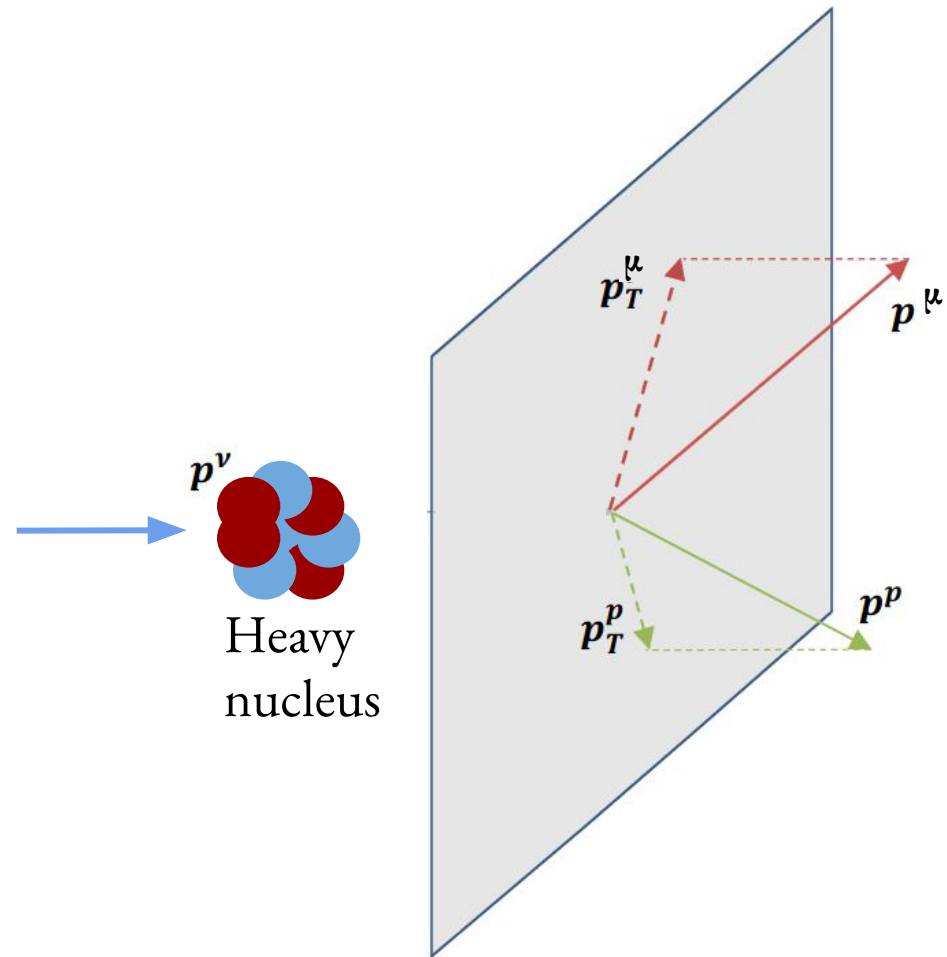
Transverse Kinematic Imbalance (TKI)



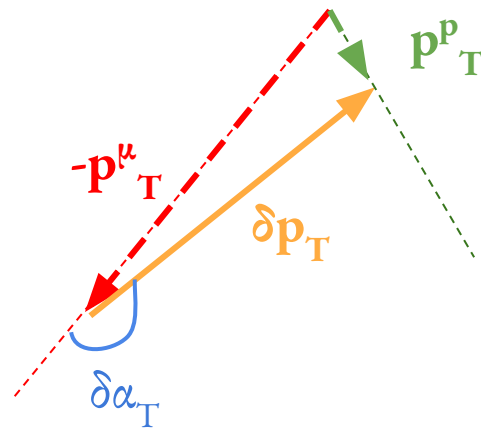
Orientation of the imbalance ($\delta\alpha_T$)
also meaningful



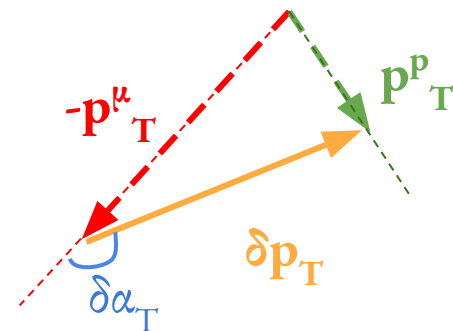
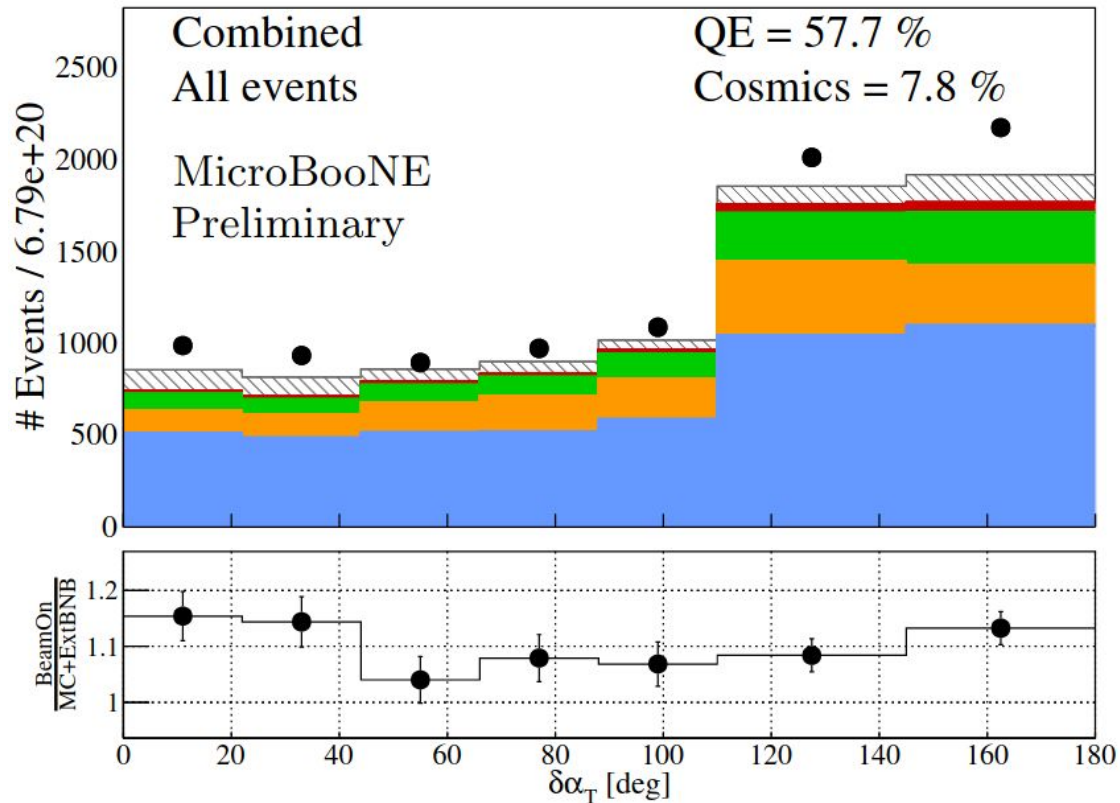
Transverse Kinematic Imbalance (TKI)



High $\delta\alpha_T$ values correspond to proton deceleration due to FSI



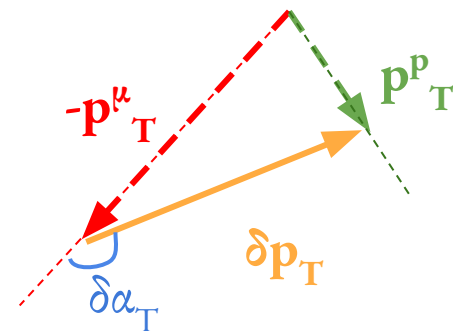
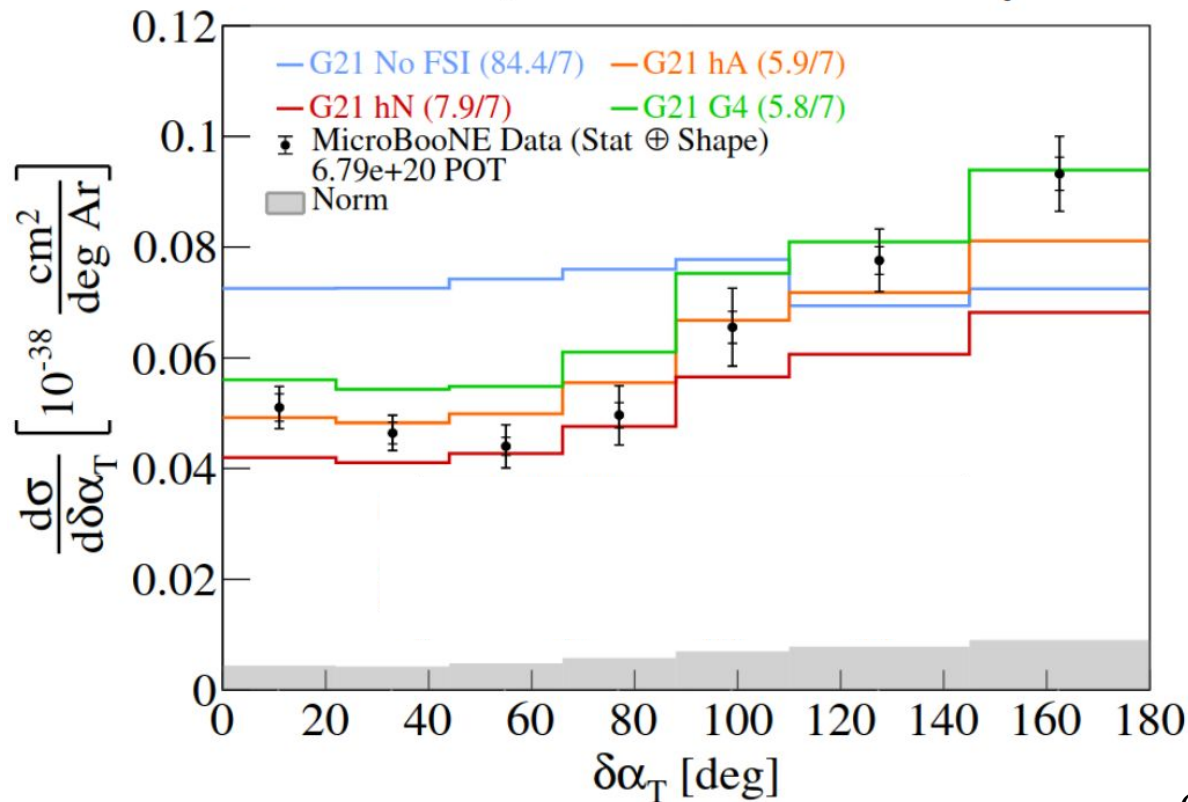
Transverse Orientation $\delta\alpha_T$



- $\delta\alpha_T$ asymmetry due to proton FSI
- **MEC/RES** fractional contribution enhanced in $\sim 180^\circ$ region

Transverse Orientation $\delta\alpha_T$ Cross Section

All events, MicroBooNE Preliminary



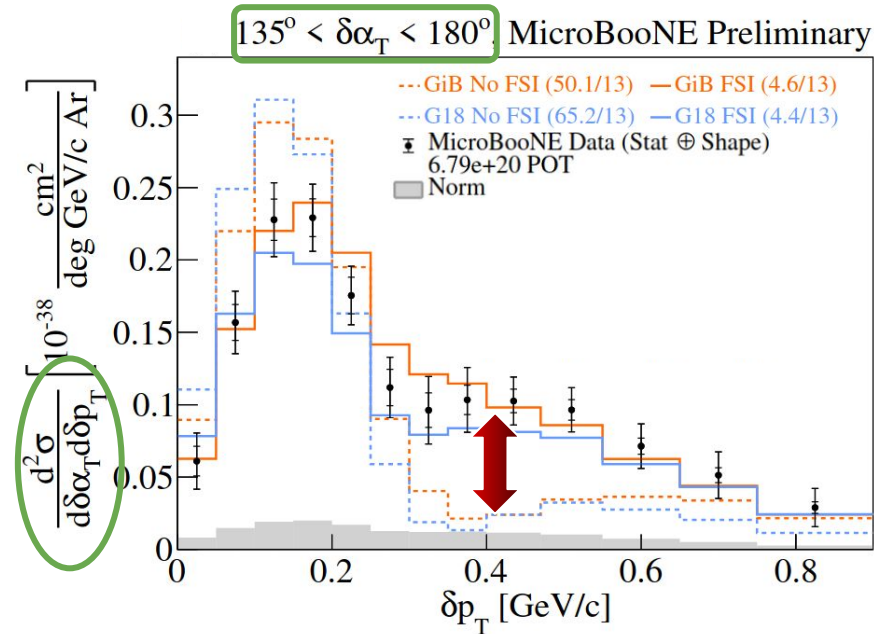
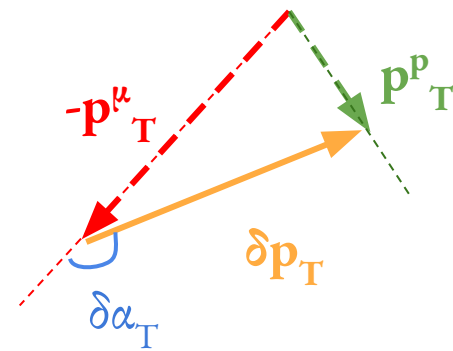
- First neutrino-argon differential cross section in $\delta\alpha_T$
- Sensitive to proton FSI modeling
- Data favors FSI addition
- Shape differences observed

G21 = GENIE v3.0.6 G21_11b_00_000

hA/hN/G4 = FSI modeling options

High Statistics → Into the Multiverse!

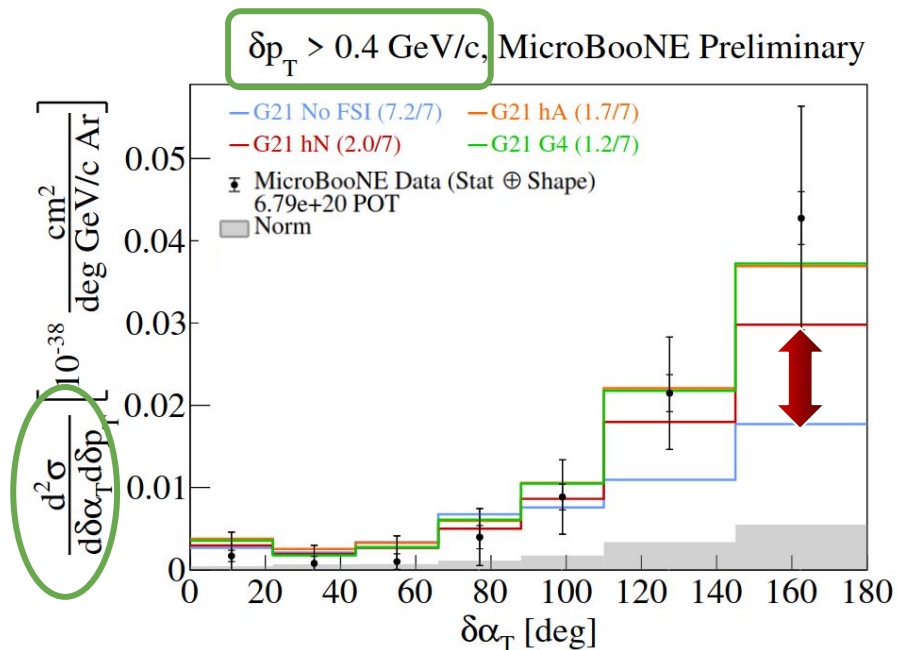
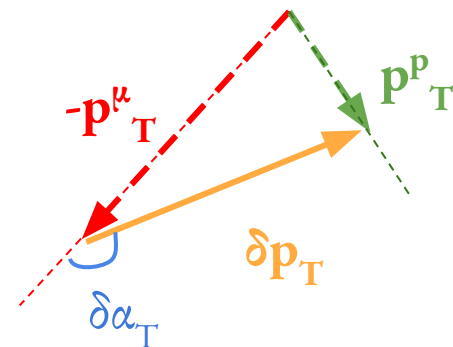
- **Extension to 2D** for the first time on any neutrino target
- Probe regions with greater model discrimination power



- FSI predictions in good agreement with data
- Minimal no-FSI contributions at high δp_T
- High $\delta\alpha_T$ & high δp_T part of phase-space ideal to test FSI / multinucleon effect sensitivity

High Statistics → Into the Multiverse!

- **Extension to 2D** for the first time on any neutrino target
- Probe regions with greater model discrimination power

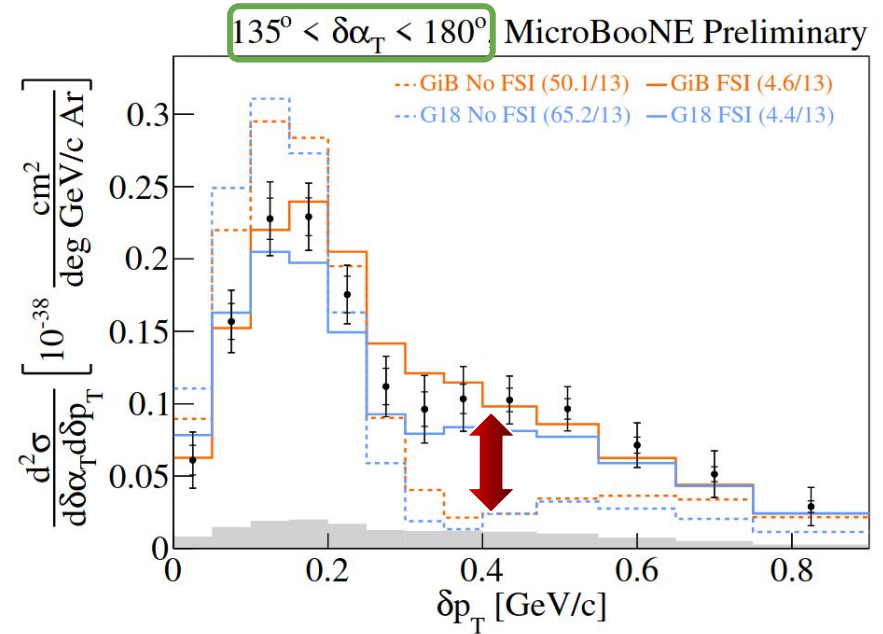


- No-FSI contribution lower than FSI ones
- High $\delta \alpha_T$ & high δp_T part of phase-space ideal to test FSI / multinucleon effect sensitivity

G21 = GENIE v3.0.6 G21_11b_00_000
 hA/hN/G4 = FSI modeling options

Summary

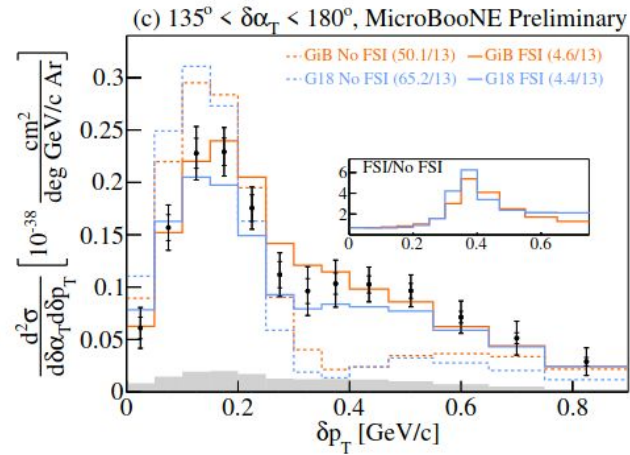
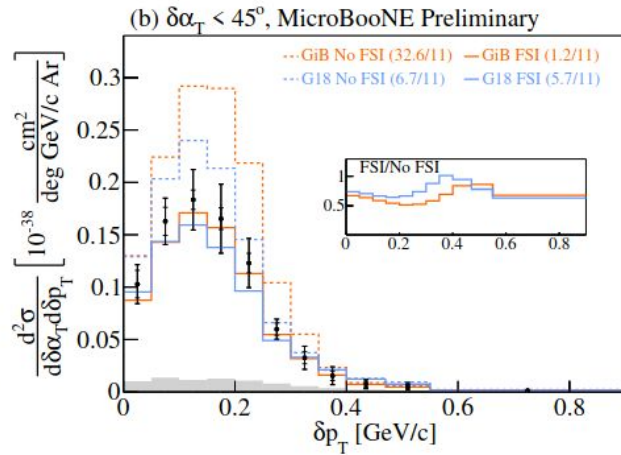
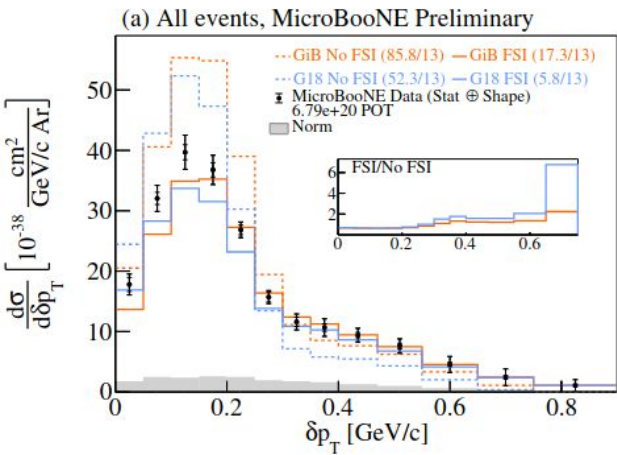
- First single-differential neutrino-argon cross section measurements in TKI
- First double-differential cross section measurement on any target in TKI
- Identified kinematic variables and phase-space regions with sensitivity to specific nuclear effects

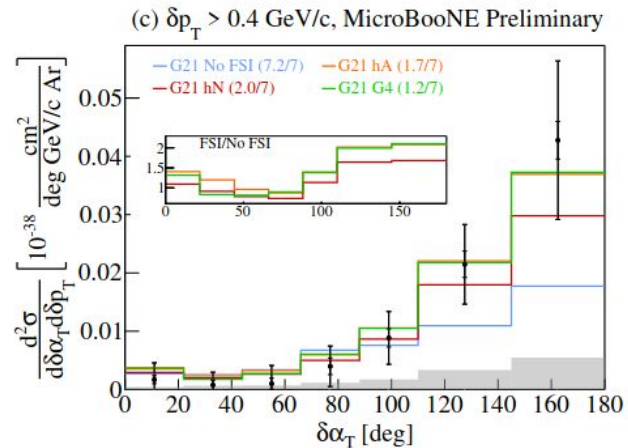
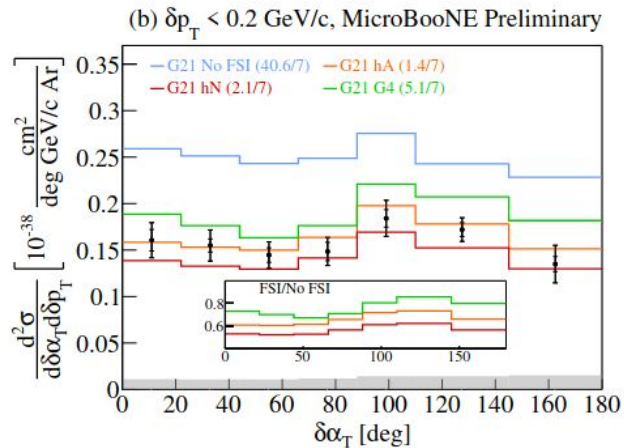
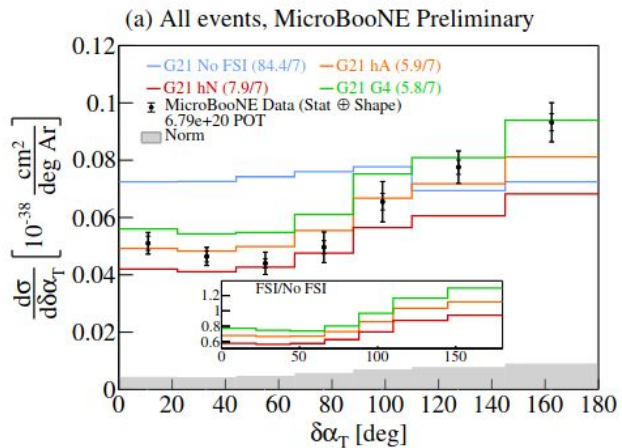


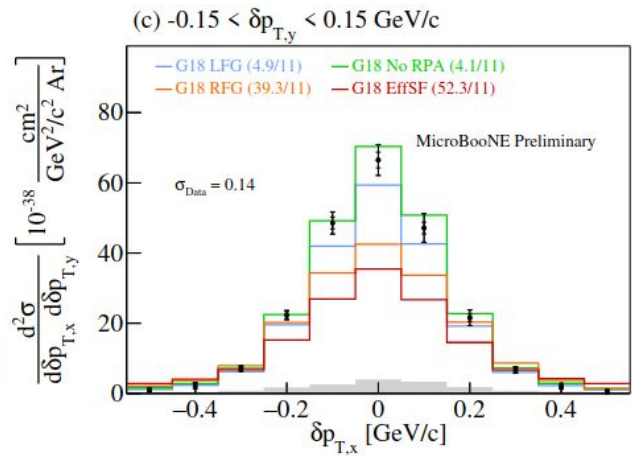
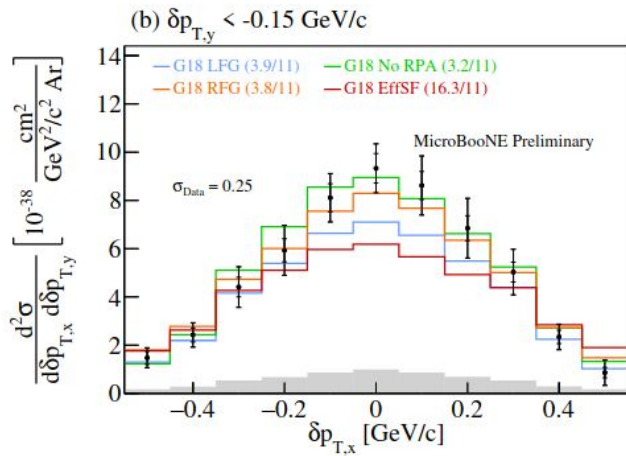
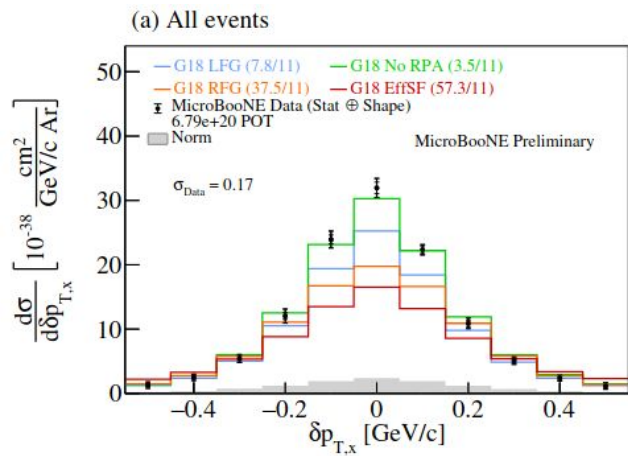


Thank you!

Backup Slides







CCQE-like vs TKI

- 1 muon $100 < P_{\mu} < \mathbf{1500}$ MeV/c
- 1 proton $300 < P_p < 1000$ MeV/c
- No π^{\pm} (> 70 MeV/c)
- No π^0 of any momenta

- $-\mathbf{0.65} < \cos \theta_{\mu} < \mathbf{0.95}$
- $\cos \theta_p > \mathbf{0.15}$

- $|\Delta\theta_{\mu,p} - 90^{\circ}| < \mathbf{55^{\circ}}$
- $|\Delta\varphi_{\mu,p} - 180^{\circ}| < \mathbf{35^{\circ}}$
- $\mathbf{p_T} = |\mathbf{p_T}^{\mu} + \mathbf{p_T}^p| < \mathbf{350}$ MeV/c

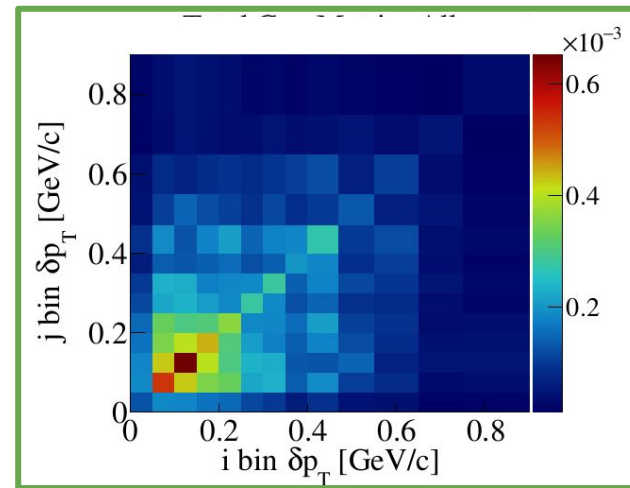
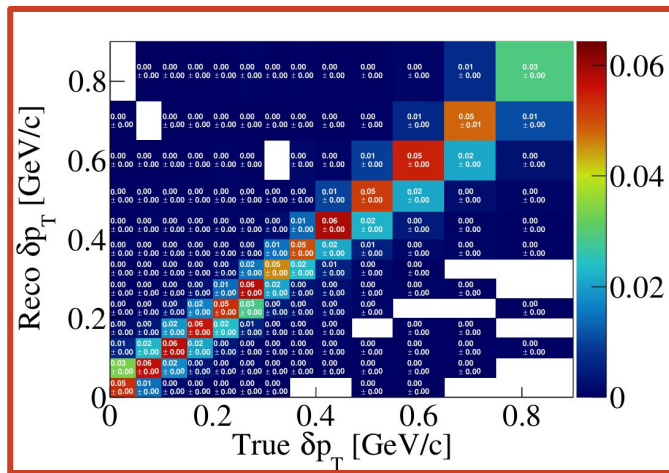
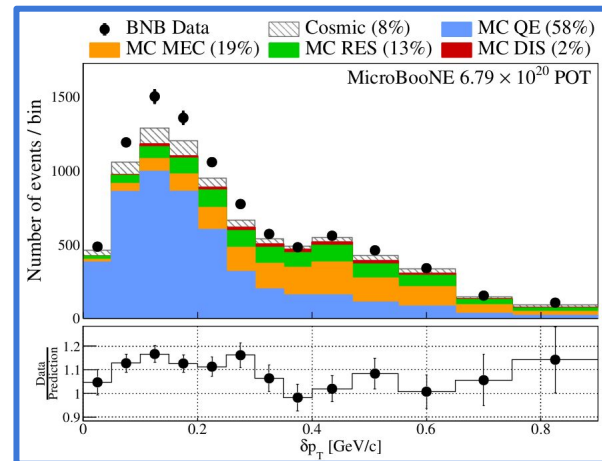
- 1 muon $100 < P_{\mu} < \mathbf{1200}$ MeV/c
- 1 proton $300 < P_p < 1000$ MeV/c
- No π^{\pm} (> 70 MeV/c)
- No π^0 of any momenta

- $-\mathbf{1} < \cos \theta_{\mu} < \mathbf{1}$
- $-\mathbf{1} < \cos \theta_p < \mathbf{1}$

Cross Section Extraction with Wiener SVD Unfolding

Input Quantities

- Measurement (Data)
- Background (MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)



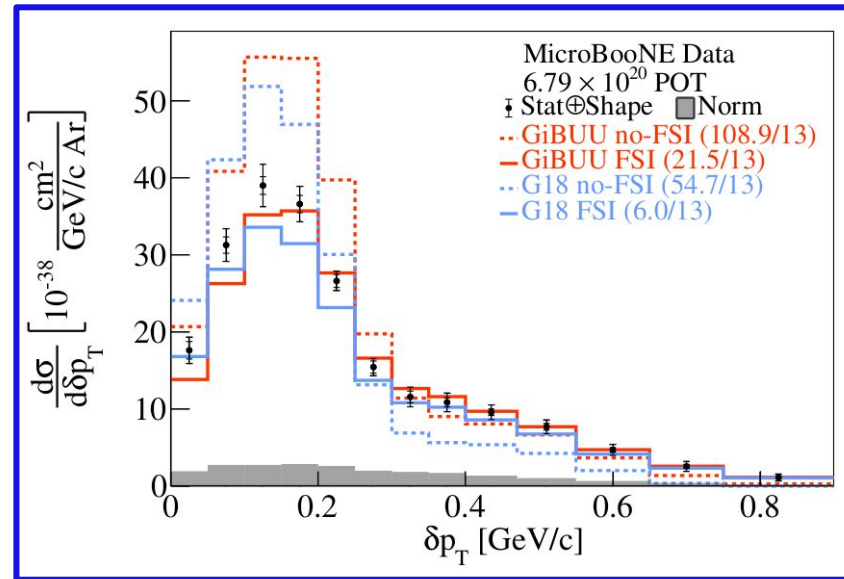
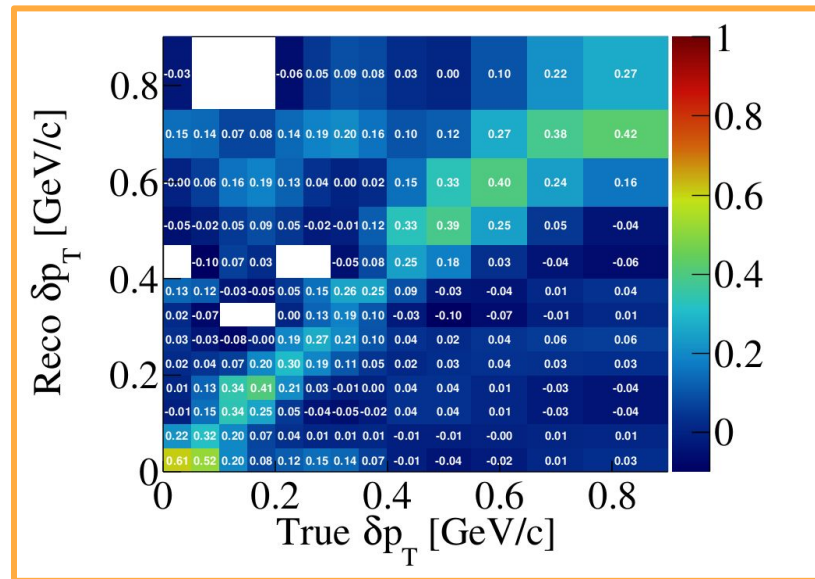
Cross Section Extraction with Wiener SVD Unfolding

Output Quantities in Regularized Space

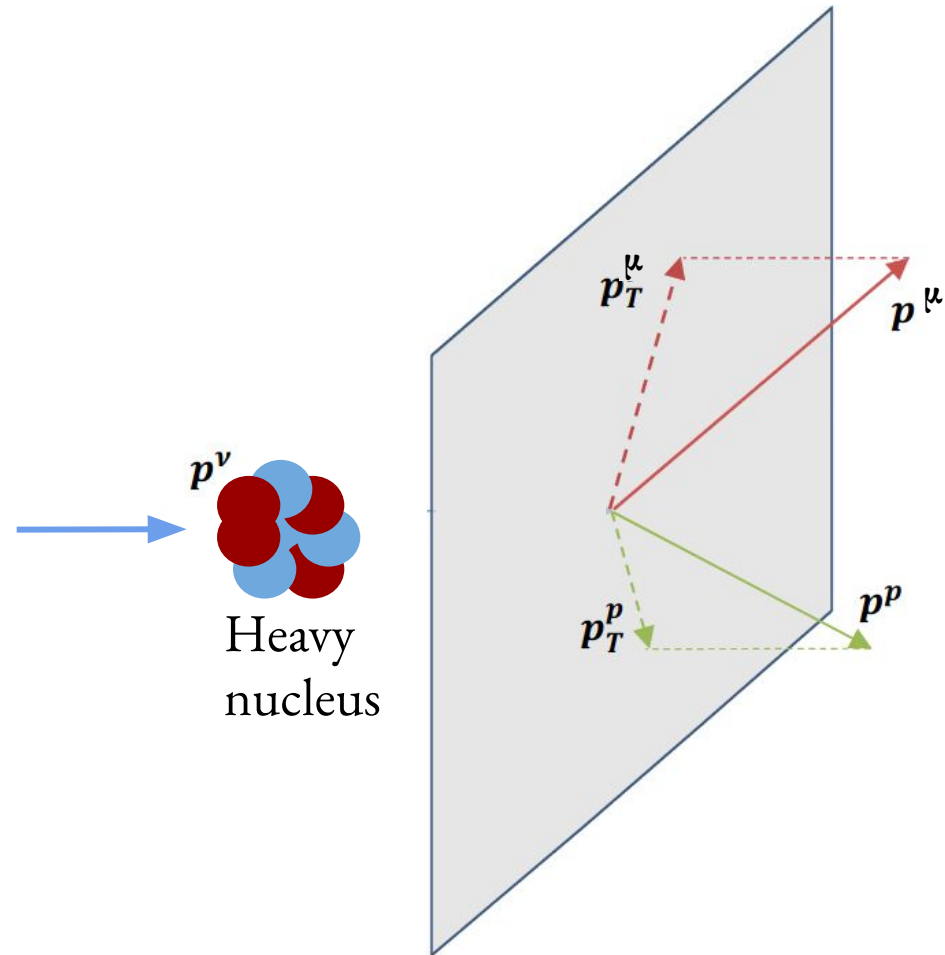
- Unfolded Data spectrum

- Smearing Matrix A_C

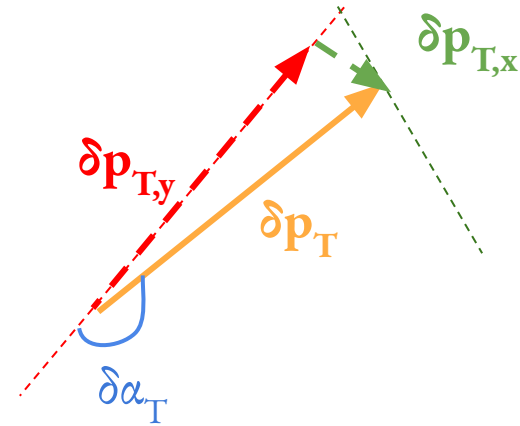
*Applied on theory predictions and included in data release



Transverse Kinematic Imbalance (TKI)

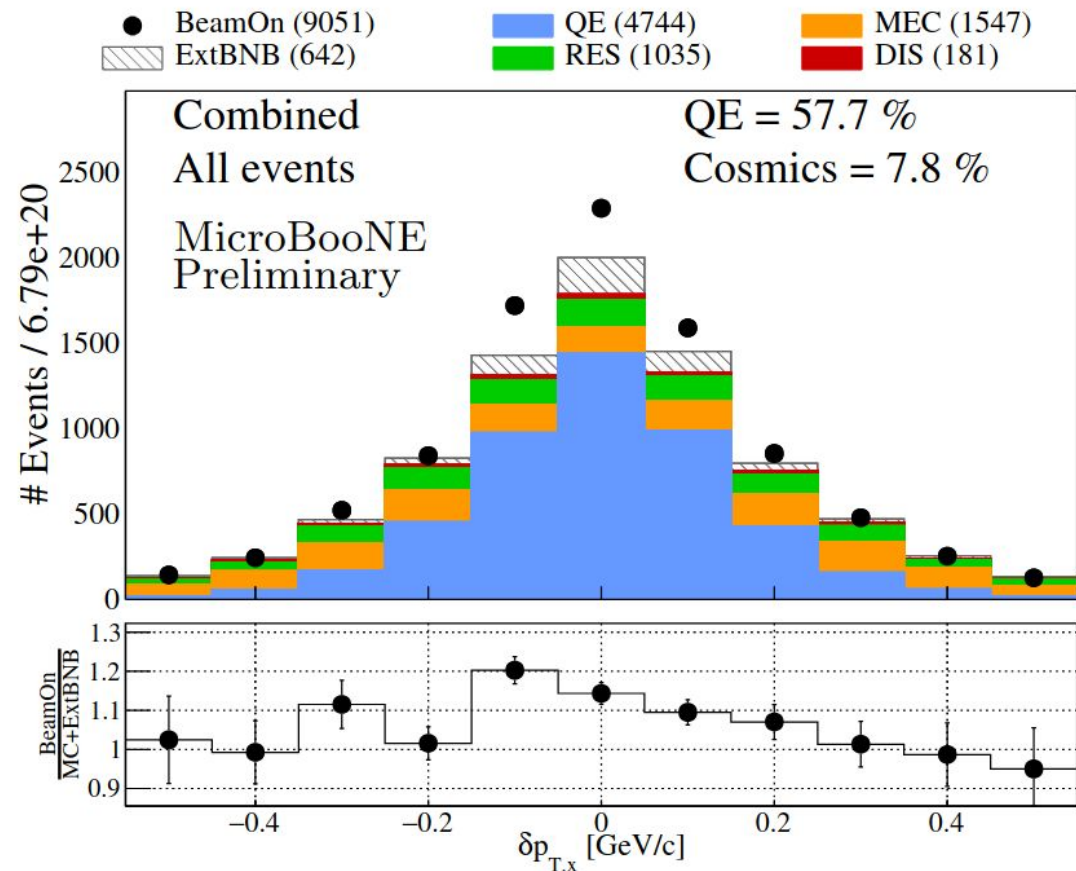
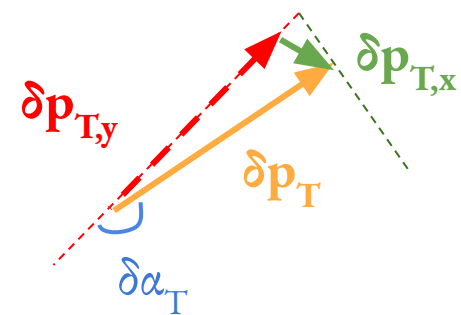


- Further handles over nuclear effects via transverse and longitudinal components



- δ -function if scattering on free nucleon
- Broad distribution due to scattering off heavy argon nucleon

Transverse Component $\delta p_{T,x}$

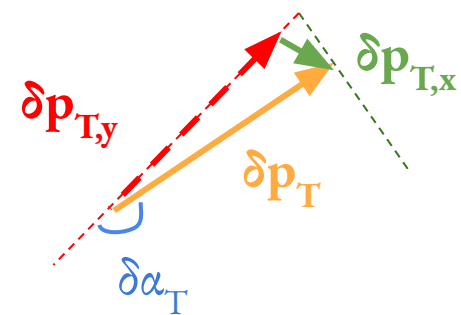
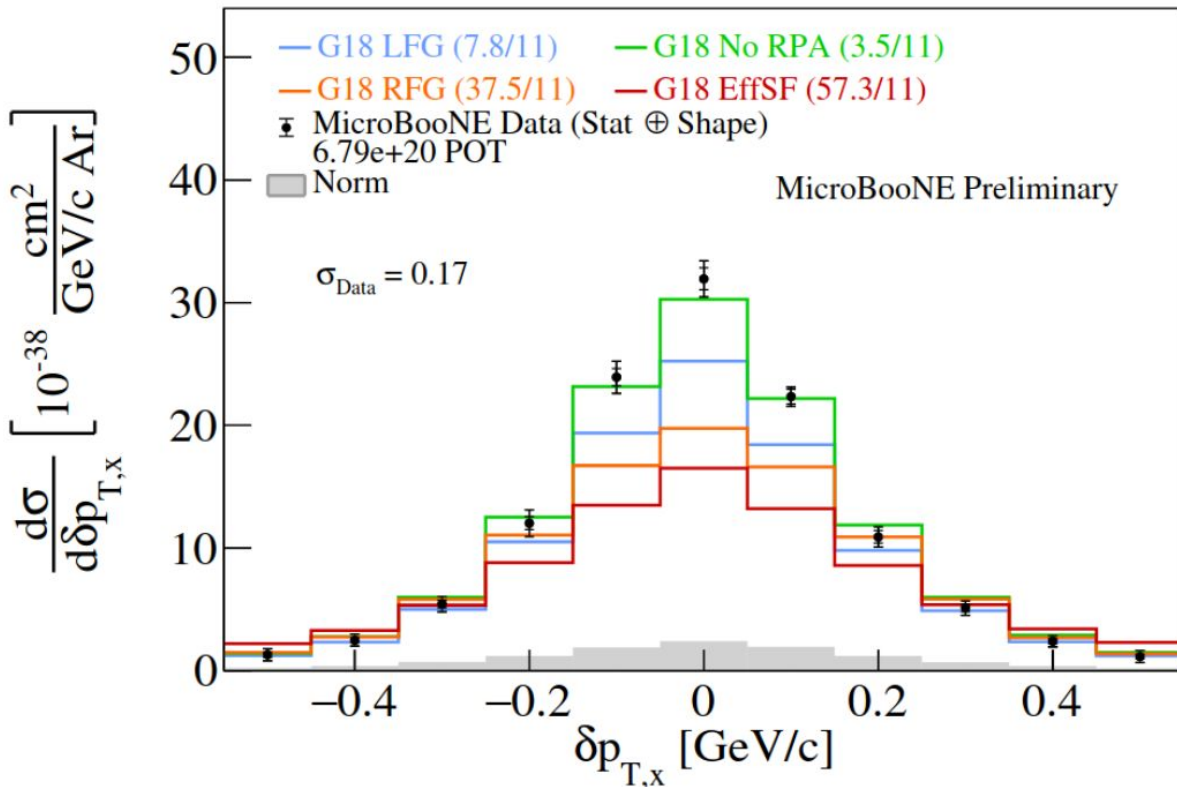


$$\delta p_{T,x} = \delta p_T \cdot \sin \delta \alpha_T$$

- Symmetric around 0 GeV/c
- **QE** dominance in central region
- **MEC/RES** events primarily in the tail

Transverse Component $\delta p_{T,x}$ Cross Section

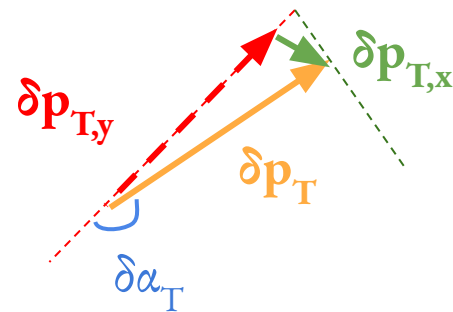
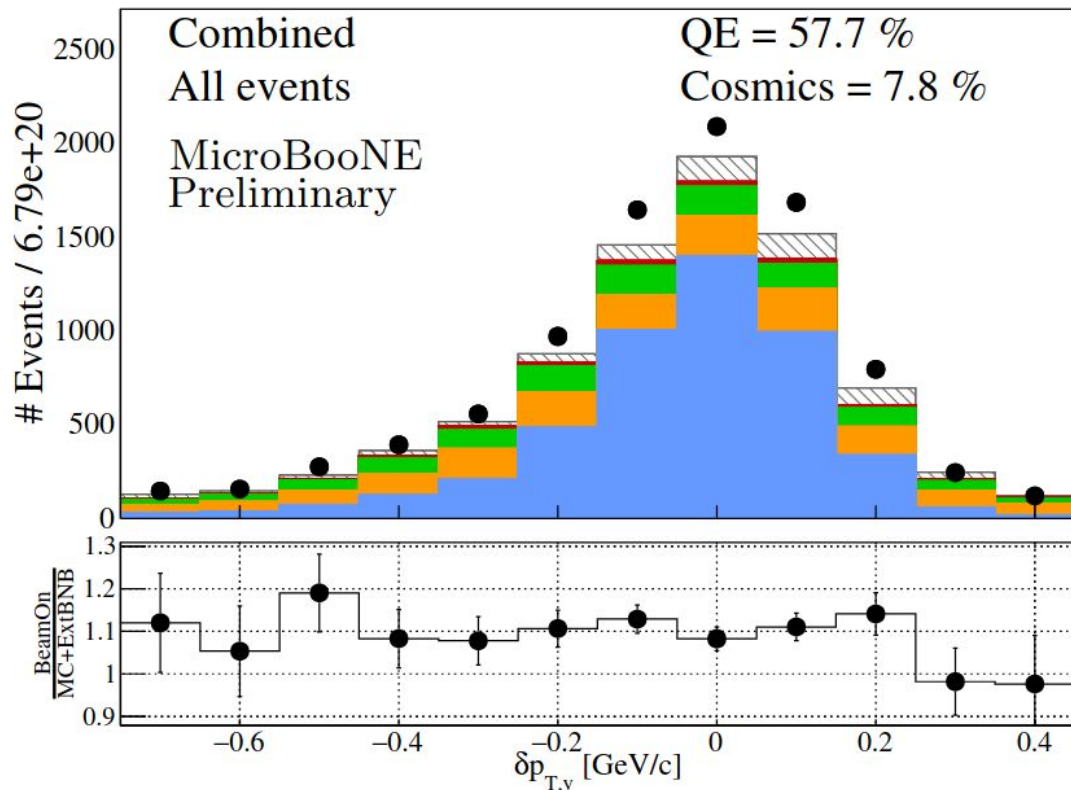
All events



$$\delta p_{T,x} = \delta p_T \cdot \sin \delta \alpha_T$$

- **G18 LFG** = GENIE v3.0.6
G18_10a_02_11a (G18) + uB Tune
with local Fermi gas
- **G18 No RPA** = G18 w/o RPA effects
- **G18 RFG** = G18 with relativistic
Fermi gas (RFG)
- **G18 EffSF** = G18 with effective
spectral function (EffSF)

Longitudinal Component $\delta p_{T,y}$

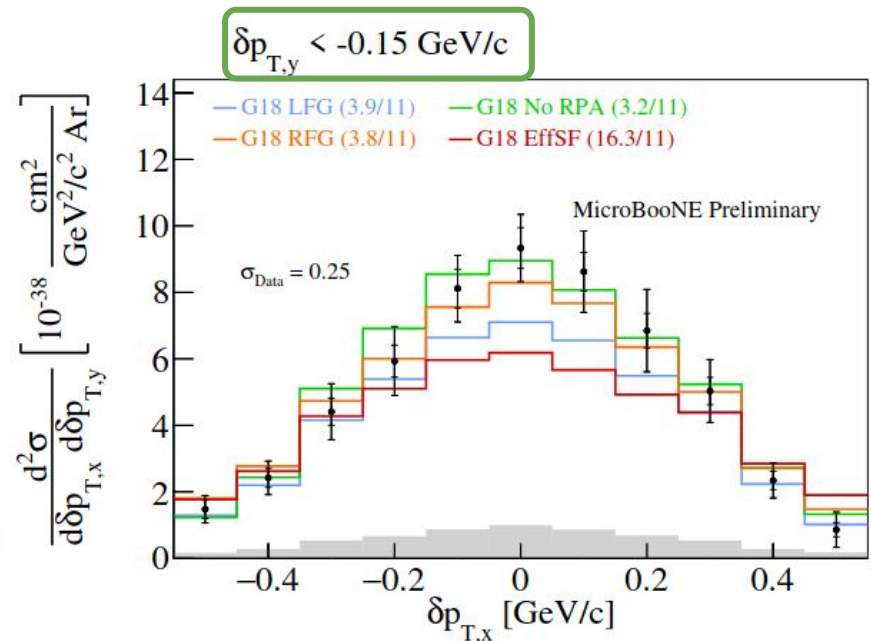
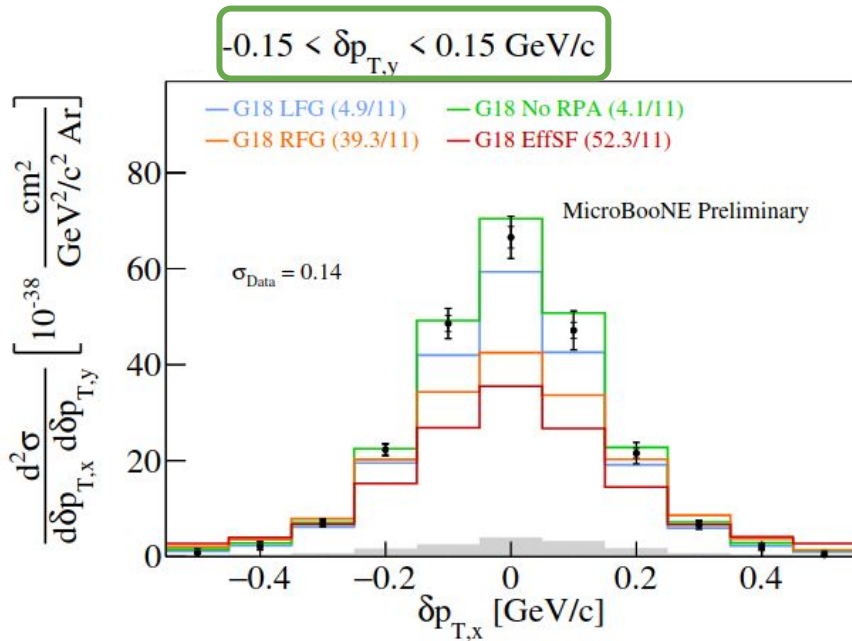
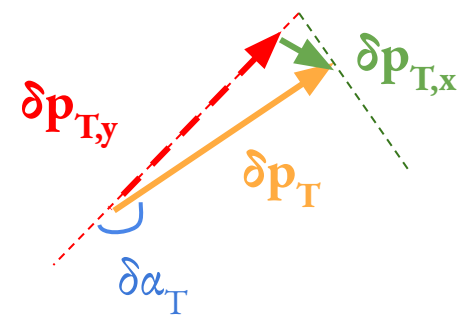


$$\delta p_{T,y} = \delta p_T \cdot \cos \delta \alpha_T$$

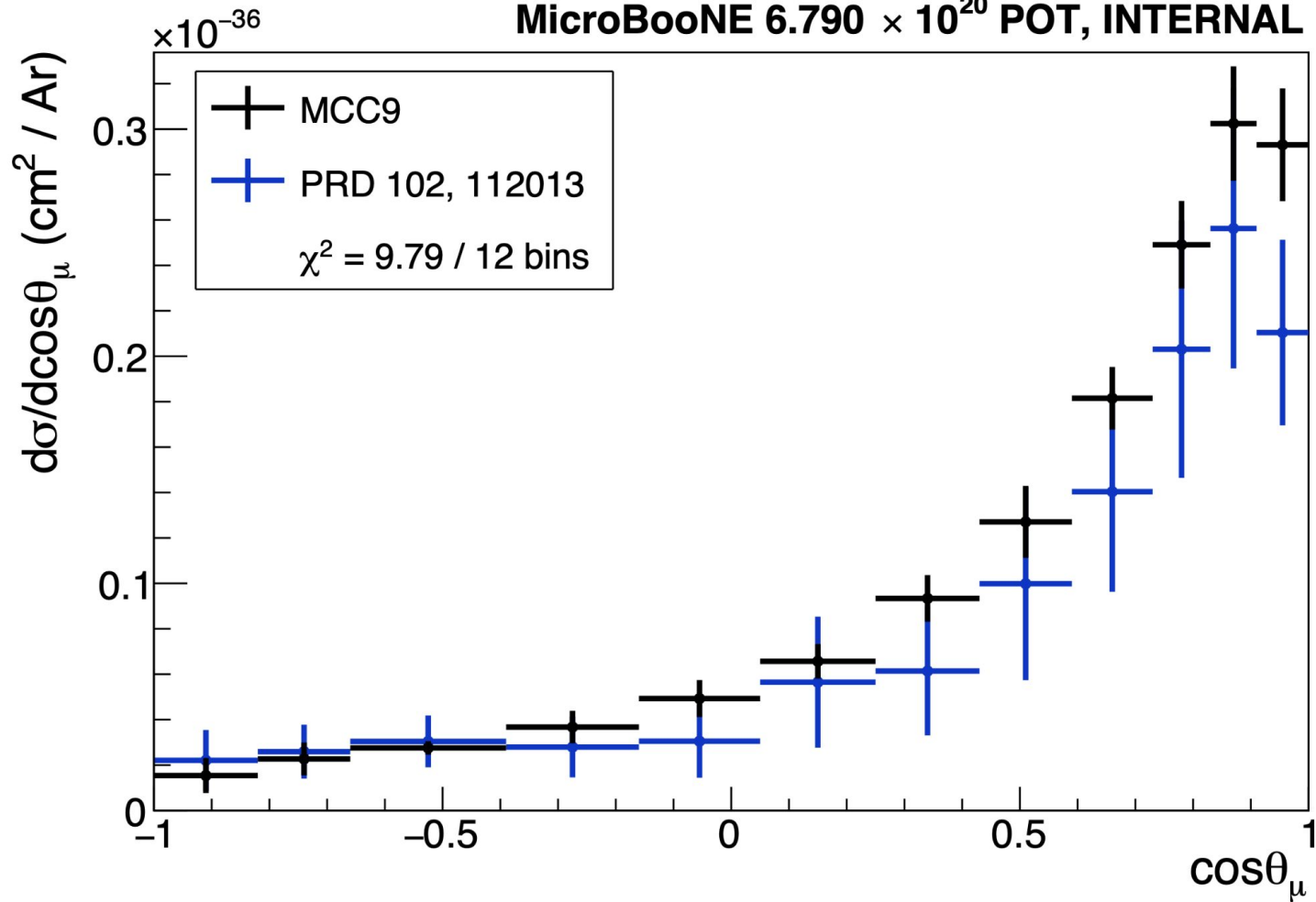
- Asymmetric due to $\delta \alpha_T$ enhancement at $\sim 180^\circ$
- Spread of tail sensitive to FSI strength & **MEC/RES**

High Statistics → Into the Multiverse!

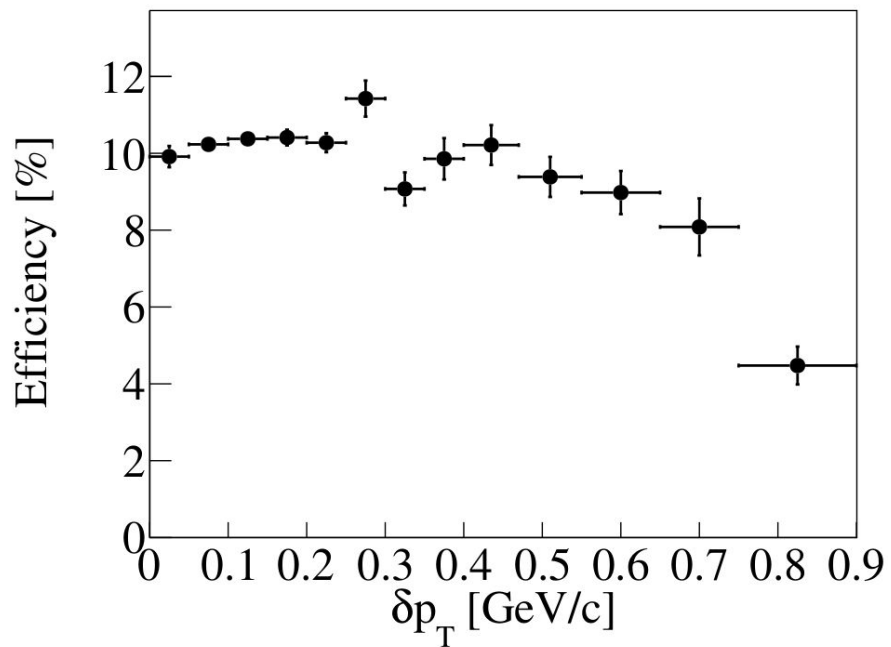
- First neutrino-argon differential cross section in TKI variables
- Sensitive to initial nucleon motion & proton FSI modeling



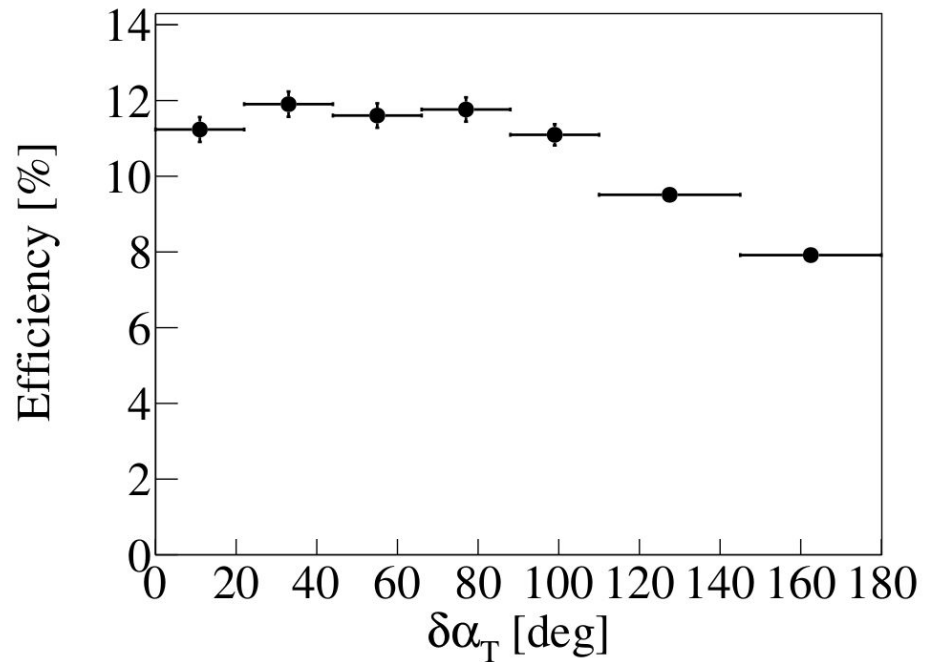
MicroBooNE 6.790×10^{20} POT, INTERNAL

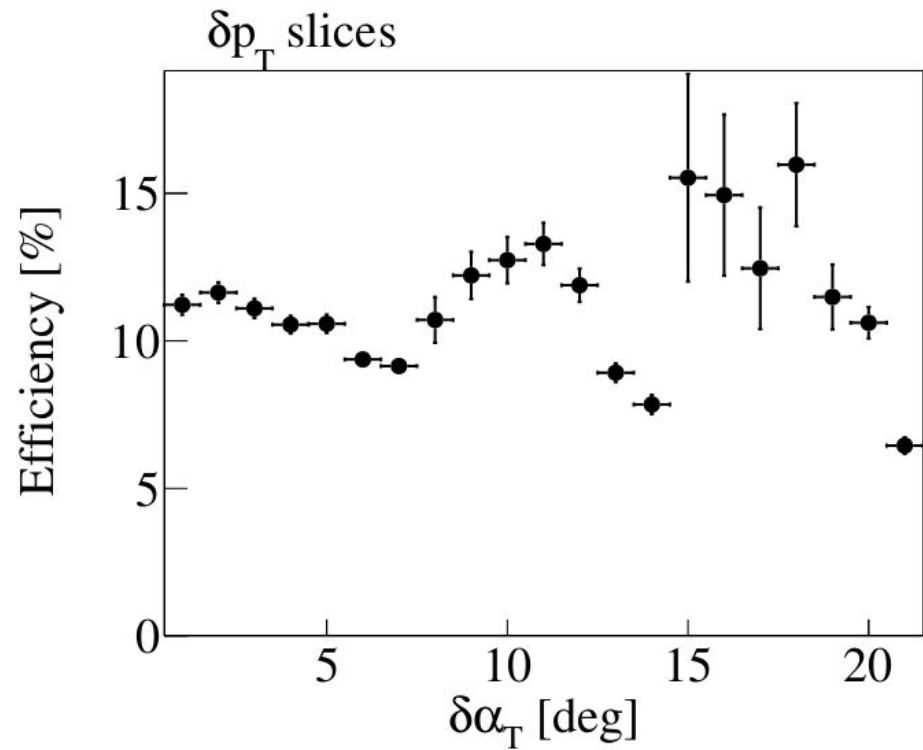
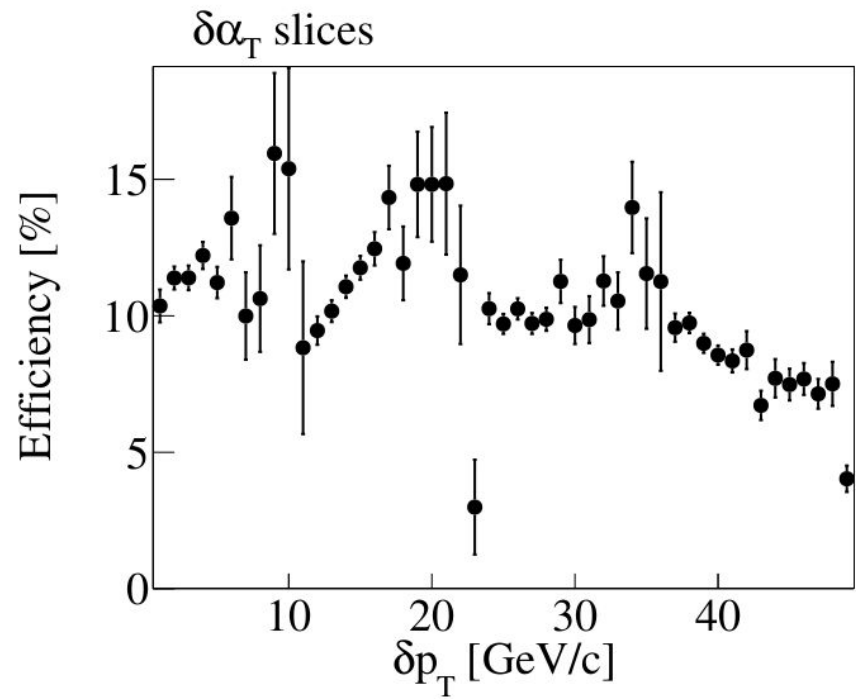


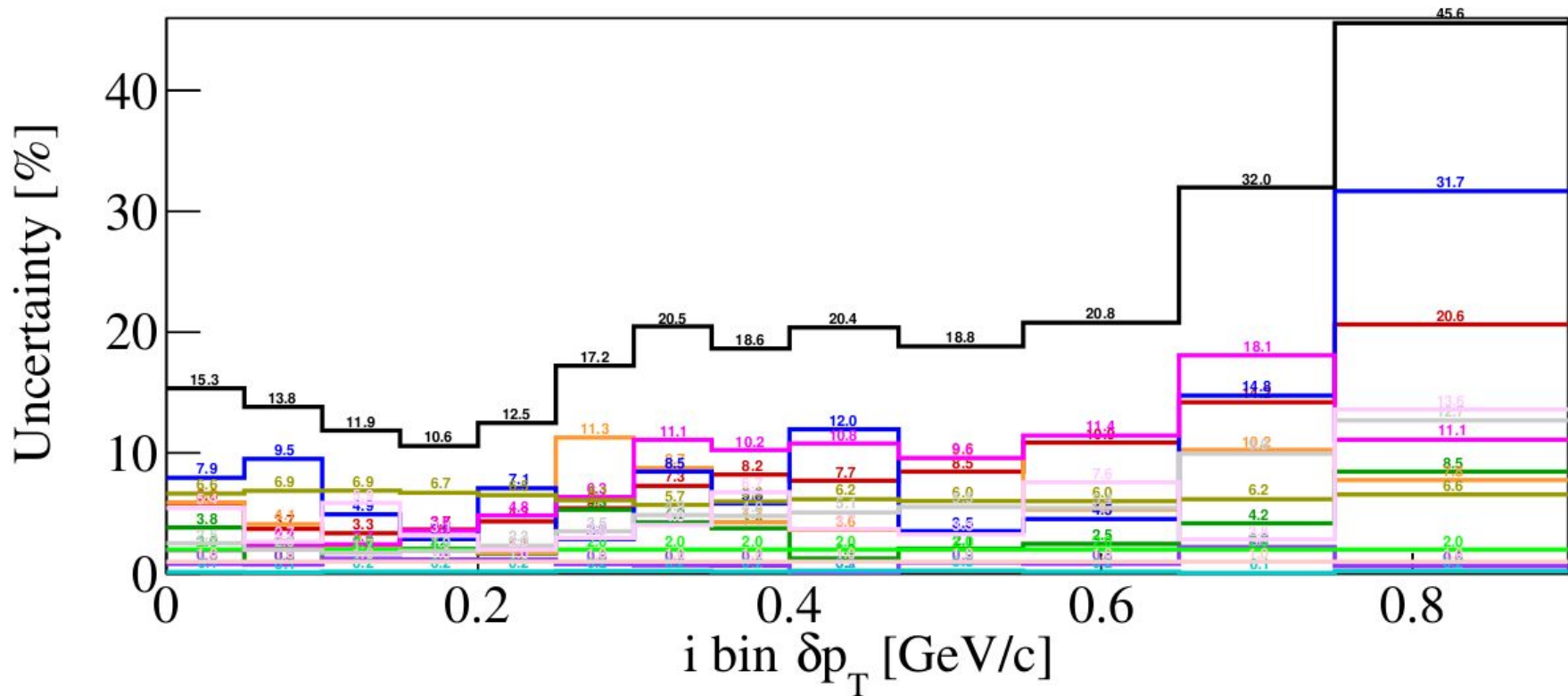
All events

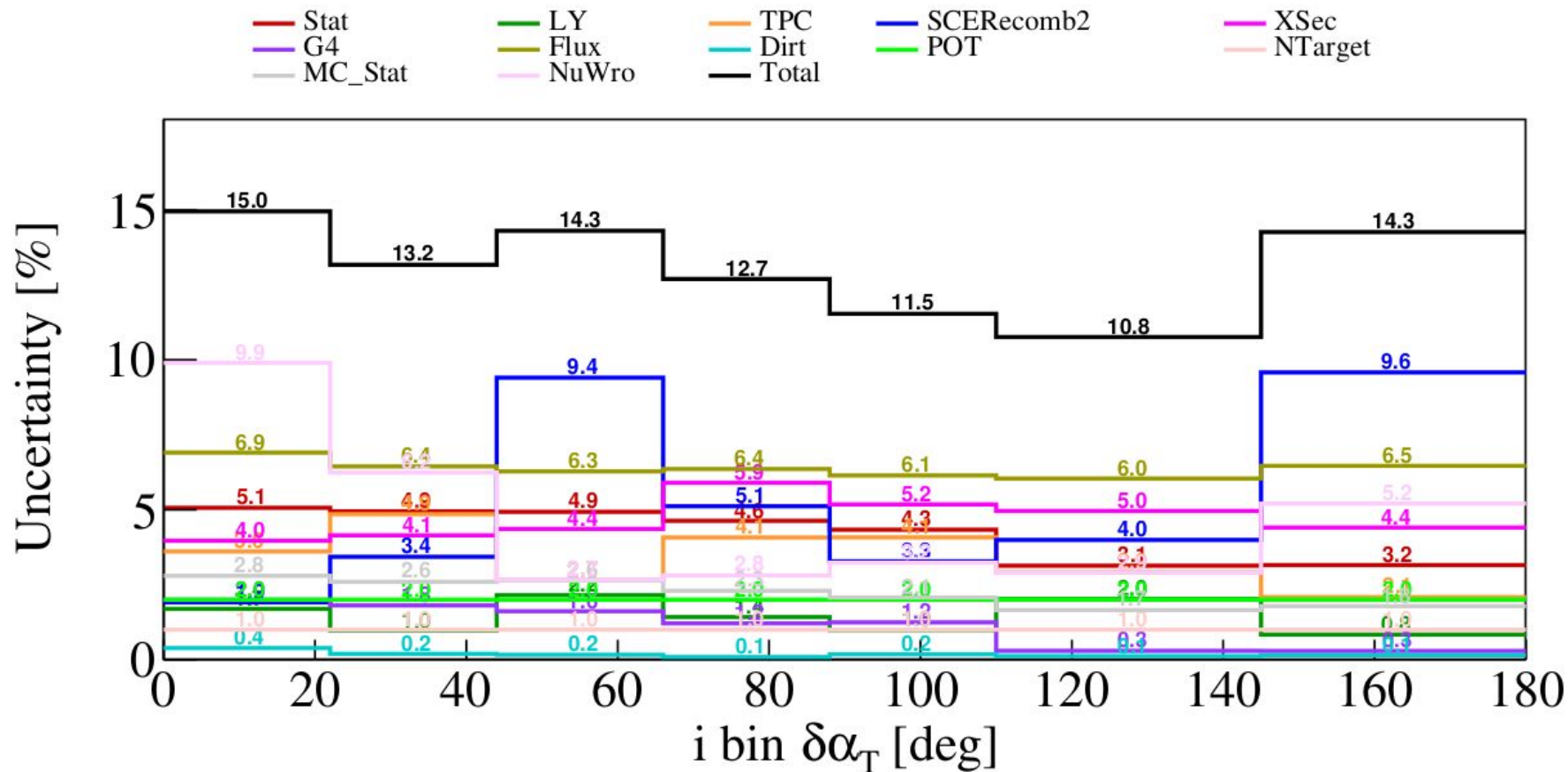


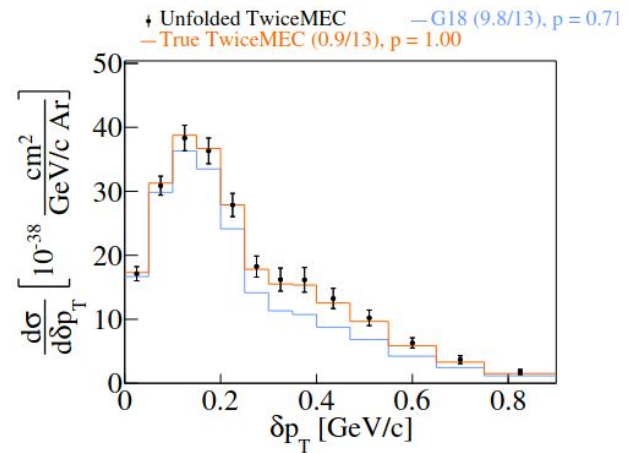
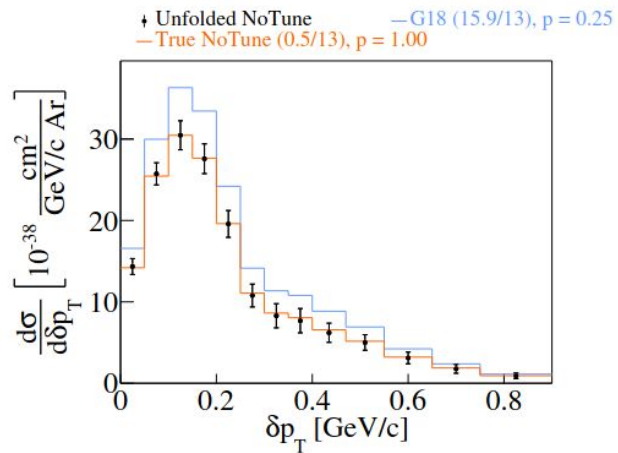
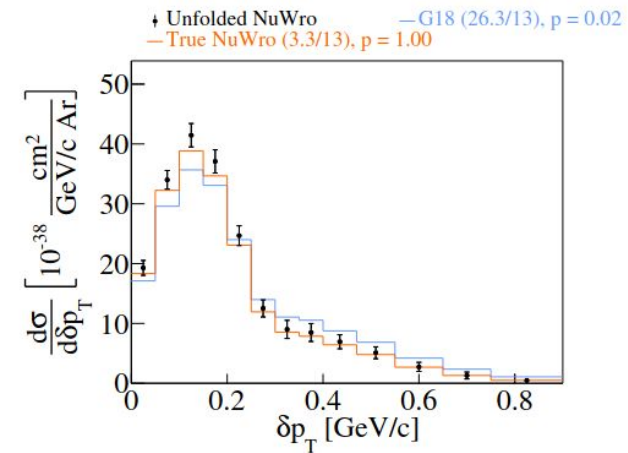
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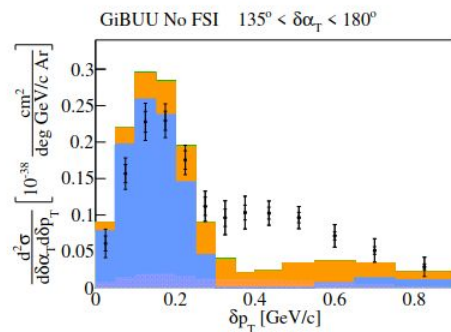
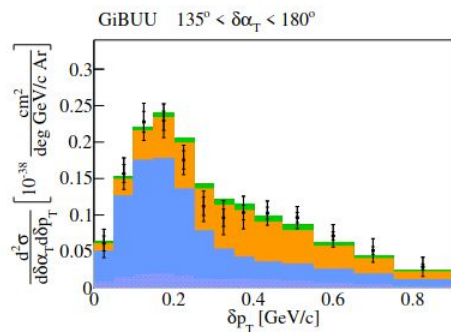
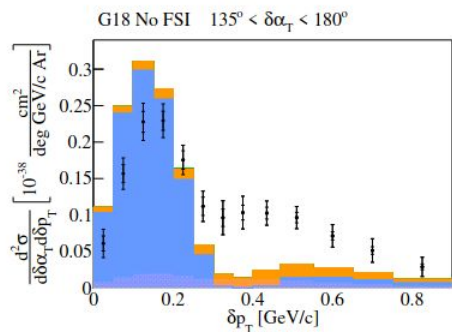
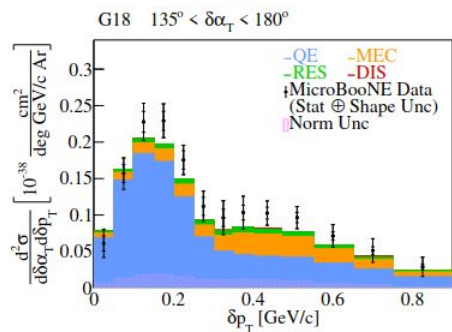
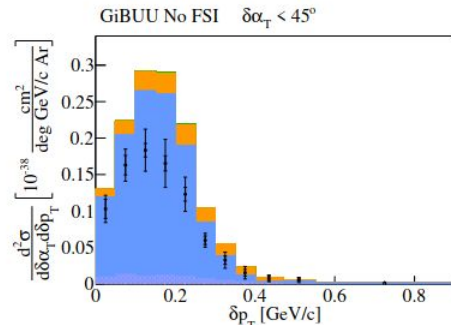
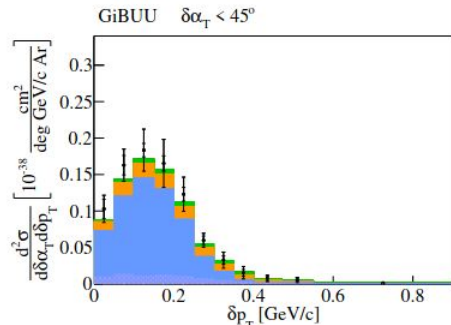
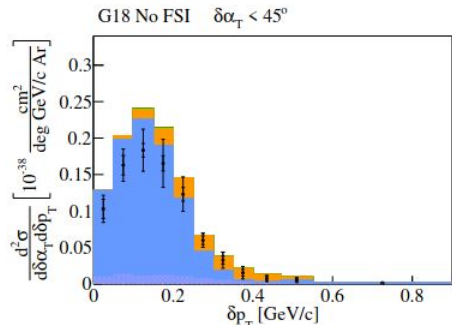
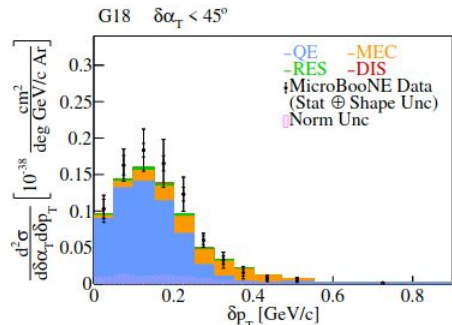
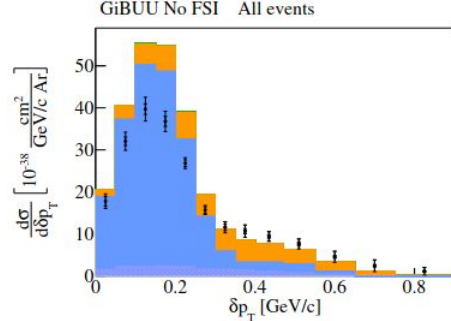
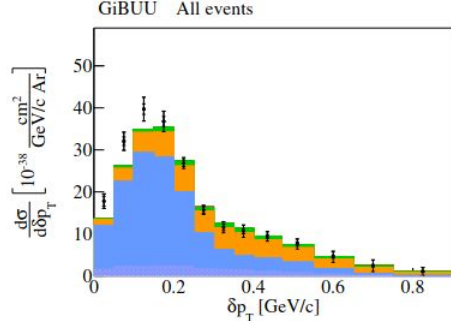
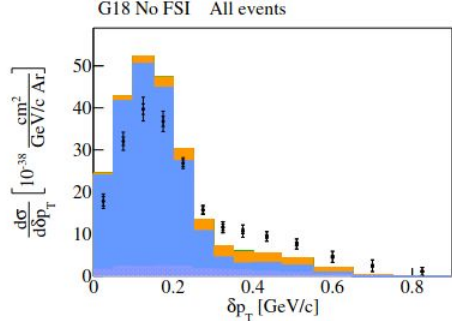
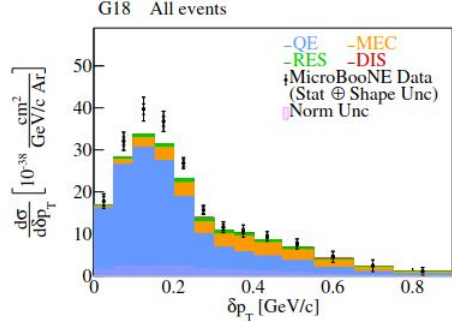












Wealth Of Results → Better Understanding of ν -Ar Interactions

CC inclusive

- ν_e CC inclusive @ NuMI (Wed.)
- ν_μ CC inclusive @ NuMI
- ν_μ CC inclusive @ BNB (Wed.)
- ν_e/ν_μ ratios @ NuMI
- E_ν, E_μ , hadronic energy @ NuMI & BNB

CC0 π

- ν_μ Single Transverse Variables @ BNB (Wed.)
- ν_μ CC2p topologies @ BNB (Wed.)
- ν_μ CC0 π inclusive @ BNB
- ν_μ CC0 π 0p @ BNB
- ν_e CC0 π Np @ NuMI

Much more coming from 30+ active analyses

Pion production

- ν_μ CC1 π^+ @ BNB
- ν_μ CC-Coherent @ BNB
- ν_μ CC π^0 @ BNB
- ν_μ NC π^0 @ BNB (Fri.)
- ν_μ CC/NC π^0 @ BNB

Rare channels

- ν_μ CC Kaon @ BNB
- ν_μ CC Kaon @ NuMI
- η production @ BNB
- Hyperon (Λ, Σ) production @ NuMI (Fri.)
- MeV-scale Physics in MicroBooNE

